

THE EFFECTS OF PRIMARY ORIFICES AND OCCLUDERS ON PROSTHETIC HEART VALVE FLUID MECHANICS

by

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ABSTRACT

The use of prosthetic heart valves, to replace defective aortic or mitral natural valves, is common practice in surgery. However, implantation of these valves can cause problems for patients. Some of these problems are directly related to the nature of the blood flow through the valves. Haemolysis, arterial wall damage, thrombus formation, tissue overgrowth and high pressure drops are the most frequently observed problems. This study aims to provide haemodynamic information about prosthetic heart valves and to give an aid for future valve design and further investigation through the determination of velocity profiles, shear stresses, and pressure drops through primary orifices. The study concentrates on the influence of primary orifices and occluders on heart valve flow.

This work was carried out experimentally using Laser Doppler Anemometry (LDA). LDA has become the most popular method in recent years for the determination of turbulent phenomena through heart valve prostheses such as shear stress, velocity profile, and the extent of stagnation and recirculation regions. Pressure taps and flow meters were used for determining pressure drops, regurgitant flow and energy losses through heart valves.

Two empirical equations were established; the first deals with the estimation of pressure losses through heart valves, and second with calculation of the effective orifice area of heart valves.

In the region downstream of a valve or orifice, jet-flow can be observed with a plugflow velocity profile, and corresponding fourth order shear stress profile. In the fully developed jet-flow region the shear stress profile is second order. Shear stress distribution depends on flow régime, and velocity profile, whereas the magnitude of shear stress is a function of axial velocity gradients and its r.m.s. component. Maximum shear stress and mean absolute shear stress occurs at the same downstream measuring plane - in the transition flow region. Pressure losses and effective orifice area of the Jellyfish valve were calculated using the equations developed to within a 5% error as compared with experimental data.

The major conclusions are:

- The orifice area is the most important factor in the causation of shear stress, pressure drops and the extent of stagnation and recirculation regions.
- The valve can be optimised by increasing the ratio of orifice area to sewing area (r_A) : the result of this study shows that as r_A increases from 0.4 to 0.75, pressure drop and shear stress reduces 10 and 70 fold, respectively. However, it is often infeasible to increase r_A due to the limitation of the valve size and sewing ring requirements: hence r_A must be optimised, whilst maintaining flow area, by adapting the orifice shape and the occluder type and position.
- The comparison of maximum velocity gradient and shear stress in heart valve prostheses at a fixed position is not practical. Mean absolute shear stress should be compared within the transition flow region of the valves.

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being available for loan and photocopying.

Vinh Tran

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There are many studies in literature which have investigated fluid mechanics of prosthetic heart valves. Therefore, this study focuses on investigating primary orifice flow with aims as follow:

- To investigate prosthetic heart valves and the effects of primary orifices on prosthetic heart valve fluid mechanics using experimental techniques.
- To establish how much of the disturbance in heart valve flow is due to orifice configuration (different area, shapes and positions of the primary orifices).
- To establish empirical equations to determine effective orifice area and pressure losses through heart valve prostheses.
- To establish the relationship between pressure drops, velocity and shear stress fields.
- To investigate the Jellyfish heart valve with measured and calculated data to check the accuracy of the model found in this study and to establish the effects of the occluder type on flow phenomena.
- Finally, to find and explain what causes the most significant disturbance in heart valve flow and give an aid for future heart valve design and recommendations for future work.

NOMENCLATURE

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Symbol	Meaning	Unit
A	sewing ring area	cm ²
Ao	tube area	cm^2
A _{Actual}	actually measured orifice area	cm ²
A _{Effective}	effective orifice area	cm ²
A _{Effective} concent	ric effective orifice area of concentric orifices	cm^2
$A_{Effective\ eccentri}$	c effective orifice area of eccentric orifices	cm^2
A _{Real}	effective orifice area (A_{Actual}) corrected via calculation	cm^2
C_s	the mean (flow parameter)component of a segment	
Ci	the instantaneous components contained within a segment	
С	discharge coefficient	
C _{Position}	position coefficient, measured and calculated	
C _{Shape}	shape coefficient	
C _P	pressure coefficient	
C_{PE}	pressure coefficient dependent primarily on eccentricity	
C _{Pr}	pressure coefficient dependent primarily on area ratio	
C_{PR}	pressure coefficient dependent primarily on Reynolds num	ber
C _{P Shape}	Pressure coefficient dependent primarily on shape	
D	tube diameter	mm
D	ball occluder diameter	mm
d	distance from lens to windows Equation 3-6	mm
d	orifice diameter	mm
d	sensor diameter	μm
d_f	laser fringe spacing	μm
Ε	eccentricity percentage	
Ε	hydraulic efficiency	
E%	relative energy loss	

f	Darcy friction factor	
$f(\pi_i)$	transformation functions	
F	focal distance	mm
i	counter: 1, 2,, <i>n</i>	
k	exponential constant in dimensionless products	
L	tube length	mm
L _{max}	maximum length of the initial jet-flow	mm
l	mixing length	mm
1	length (generally along axial axis)	mm
1	hot-wire sensor length	mm
m	number of measured cycles	
n	number of measured data points	
Ν	refractive index	
Р	wetted perimeter (Equation 5-13)	mm
Р	pressure	Pa
PI	performance index	
$P_{Downstream}$	static pressure in the downstream region	Pa
P_d	dynamic pressure	Pa
P _{Maximum}	upper limit of pressure transducer range	kPa
P_s	static pressure	Pa
P_t	total pressure	Pa
P _{Upstream}	Static pressure in the upstream region	Pa
Q	flowrate	m ³ /s
Q	flow volume in pulsatile flow	m^3
q	flowrate in pulsatile flow	m ³ /s
$Q_{Regurgitant}$	regurgitant flow volume	m ³
Q%	relative regurgitant flow	
r	pertaining to the radial direction	
r	correlation factor	
r	radial position	mm
r _A	ratio of orifice area to tube area	
Re	Reynolds number	

S	slope of ΔP and Q^2/d^4 relationship; Equation 2-2	
t	thickness of the window	mm
Т	time of a cycle	S
T_{I}	time of period of forward flow (systole)	S
T_2	time of period of closing phase	S
T_3	time of period of closed phase	S
TI	turbulence intensity	
U	time averaged velocity	m/s
U	mean axial velocity	m/s
и	instantaneous axial velocity	m/s
u'	fluctuating axial velocity	m/s
u'_1 and u'_2	fluctuating velocities measured at ±45° relative	
	to axial direction	m/s
ν	instantaneous tangential velocity	m/s
v'	fluctuating tangential velocity	m/s
V	mean tangential velocity	m/s
w	instantaneous radial velocity	m/s
w'	fluctuating radial velocity	m/s
W	mean radial velocity	m/s
x	distance in axial direction	m
x	pertaining to axial direction	
α	half angle of two laser beams intersection	
α	angle of laser beam with normal direction of a surface	
δ	partial differential	
δ%	accuracy of pressure transducers	
δΡ	absolute error of pressure transducers	kPa
Δ	denotes a difference or gradient	
ΔE	energy loss	W
ΔP	pressure drop	Pa
ΔP_0	overall pressure loss	Pa
θ	pertaining to the tangential direction	

Φ_{Shape}	shape factor	
λ	wavelength of laser light	nm
μ	dynamic viscosity	Pa s
ν	kinematic viscosity	m²/s
π_d	dependent dimensionless product	
$\pi_1, \pi_2,, \pi_n$	independent dimensionless products	
ρ	density	kg/m ³
σ_U	axial velocity standard deviation	m/s
σ_V	tangential velocity standard deviation	m/s
τ	shear stress	Pa



1.1 General introduction

The human heart is the organ in the human body which plays the most important role in circulating blood around the body. The heart in conjunction with heart valves causes the blood to flow in one direction and dysfunction of the heart or heart valves can be fatal. Open heart surgery is common practice in remediation of these conditions - where the heart or valves may be replaced or repaired. Minor cardiac surgery and heart valve remediation have been practiced for seventy years or so; the first successful heart treatment was dilation of a stenotic mitral valve using the fingers. This was performed by Souttar in 1925. Following the advent of heart-lung bypass machines, open heart surgery enabled heart valve replacement and donor organs transplantation. The first prosthetic heart valve was implanted successfully in humans by Starr and Edwards in 1960 (Starr and Edwards, 1961) and nowadays, prosthetic heart valve implantation is widespread and common clinical practice in medical centres and nearly 75,000 prosthetic heart valves are implanted in humans annually throughout the world.

Though prosthetic heart valves have been used for a long time, cardiac patients still continue to suffer from numerous pathological problems. These problems are directly related to the fluid dynamics of artificial heart valves. For example, high shear stresses cause haemolysis and endothelial damage (Hellums *et al.* 1977), stagnation, recirculation regions and low shear rate may lead to thrombus formation and tissue overgrowth, and high pressure gradients cause high energy loss and may lead to dysfunction of the heart (Hanle *et al.* 1989). In these cases, fluid dynamics plays a very important role in understanding and analysing the pathological problems of these prostheses.

The presence of the prosthesis disturbs the flow of blood producing areas of high shear stress, high wall stress and separated flow regions, which cause pathological problems to the valve's recipient. The sewing ring and occluder are the two main components of a prosthesis which cause the greatest stenosis and obstruction. The intensity of flow disturbance through heart valves strongly depends on structure and geometry of the sewing ring and occluder.

It is evident, that investigating the fluid dynamics of heart valve flow is a very important stage in designing a heart valve. There are two major methods for investigating fluid dynamics of heart valve prostheses, viz computational and experimental. The computational techniques can provide a full picture and relatively good approximations of velocity and stress distributions in a flow field. However, the limited memory capacity of contemporary computers impedes them in giving accurate results, especially in complicated flows and flows in intricate geometries. Measurements using experimental techniques, especially using Laser Doppler Anemometry (LDA) techniques in heart valve flow, provide much valuable and accurate information of flow through heart valves in both steady and pulsatile flow conditions. However, such experimental techniques can not provide a full picture of the flow or the distribution of turbulent flow phenomena.

This study was carried out using experimental techniques. Heart valve flow was examined by investigating primary orifice flows. The effects of the orifice area, orifice shape, and orifice and occluder position on velocity and shear stress fields and pressure drops across heart valves were investigated. Pressure drops across orifices were measured using pressure taps, and analysed using dimensional analysis to establish empirical equations such as pressure coefficient and effective orifice area for comparison of several heart valves. Instantaneous velocities were measured using LDA, from which shear stresses and turbulence intensities were calculated.

The aims of this study were to:

- investigate prosthetic heart valves and the effects of primary orifices on prosthetic heart valve fluid mechanics using experimental techniques
- establish how much of the disturbance is due to orifice configuration (different area, shapes and positions of the primary orifices)
- establish empirical equations to determine effective orifice area and pressure losses through heart valve prostheses
- establish the relationship between pressure drops, velocity and shear stress fields
- investigate the Jellyfish heart valve with measured and calculated data to check the accuracy of the model developed in this study and to establish the effects of the occluder type on flow phenomena
- explain what causes the most significant disturbances in heart valve flow and give an aid for future heart valve design and recommendations for future work.

1.2 Description of the human heart and its valves

The heart is a very important organ functioning as a pulsatile synchronous pump which beats about 72 times each minute and transports about 6 l/min of blood at rest to about 25 l/min during extreme exertion. The heart with the lungs provides the oxygen requirements of the human body by maintaining the circulation of blood. There are two separate circulations, a greater or systemic circulation through the body, and a lesser or pulmonary circulation through the lungs. The purpose of the systemic circulation is to carry oxygen and nourishment to all parts of the body and to remove carbon dioxide and other waste products of metabolism from tissues. The purpose of the lesser circulation is to carry deoxygenated blood from the right

ventricle to the lungs where its carbon dioxide is liberated and oxygen absorbed (see Figure 1-1).



Figure 1-1 Human heart with two circulations

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The heart has four chambers: two ventricles and two artria. The two ventricles are pumping chambers and the two artria are receiving chambers. Corresponding to the four chambers, the human heart has four valves: aortic, mitral, tricuspid and pulmonary. The action of these four heart valves within the heart restricts blood flow to one direction and prevents substantial backflow.

Blood returning from the body is deoxygenated and flows through the venae cavae to the right atrium. This blood flows further through the tricuspid valve into the first pumping chamber called the right ventricle. Blood in the right ventricle is pumped through the pulmonary valve and the pulmonary artery into the lungs where the blood becomes oxygenated. Blood then flows into the left atrium, then fills the left ventricle through the mitral valve. This filling phase of the cardiac cycle is called

diastole. When the diastolic cycle is finished, the left ventricle contracts abruptly, the mitral valve closes and blood is pumped through the aortic valve. This phase of the cardiac cycle is called ventricular systole. Left and right ventricular systole occur simultaneously as do left and right diastole. Pressures on the left side are 5 times greater than those on the right side, hence the left hand valves (mitral and aortic) fail more readily. As a result, both mitral and aortic incompetence are common valvular defects (a valve is incompetent when it fails to close properly, producing a jet of blood to flow retrogradely through the valve when it should be shut). Another common valve defect is stenosis. This is a narrowing of the valve which impedes forward flow of blood through the valve. Both of these conditions are indications for valve replacement.

In the natural heart, the valve leaflets open at the centre to allow unobstructed central flow. The aortic and pulmonary valves are outlet valves, each consisting of three cusps attached to a fibrous tissue ring on the inner walls of the aorta and pulmonary artery respectively. Both outlet valves have similar dimensions. The mitral and tricuspid valves are inlet valves, the tricuspid valve has three similarly sized cusps whereas mitral valve has one major leaflet and one minor leaflet.

1.3 Outline of the present study

This study focuses on the disturbance caused by primary orifices in prosthetic heart valve fluid flow and the effects of the structure of the orifice and occluder on the fluid dynamics of the valve. Chapter One presents the most general introduction, the aims of this study, the human heart, heart valves and their functions in the human body.

In Chapter Two, the literature is reviewed. Details of heart and heart valve prostheses can be observed, such as the most commonly used heart valves, the history and development of heart valve prostheses, and surgery. Problems related to heart valve fluid dynamics are analysed briefly in *section 2.4* to impress the

importance of investigating heart valve fluid dynamics for the development of future valve design. Furthermore, orifice and heart valve flows are reviewed, *in-vitro* measurements made by several investigators of flow through different heart valves are analysed and compared in terms of fluid dynamics, and in conjunction with the structure of each valve. This leads to the conclusion that the valve configuration is an important factor to affect fluid flow downstream of the valve. The review of orifice flows and their further investigations may explain the disturbance caused by the presence of different valve configurations in blood flow. Finally, conclusions leading to objectives of this study are drawn and presented.

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Chapter Three is concerned with the methodology and instrumentation which were needed for this study. Firstly, several methods are reviewed and compared allowing the choice of the one which was the most appropriate for this study. Experimental methods using LDA (Laser Doppler Anemometry) pressure and flow measurement techniques were chosen for this study. LDA has recently become the most commonly used technique for measuring turbulence phenomena in fluid flow, especially in heart valve flow. Several experimental set-ups and instruments which were used for this study are presented and described.

Data analysis in this study is a vital stage in presenting and clarifying the work, as this study was carried out experimentally. Chapter Four mentions some analysis techniques and equations used to analyse pressure drop, LDA velocity measurements and their products in both steady and pulsatile flows, eg. a 5° binning analysis was used for pulsatile flow data to calculate mean and fluctuating components; dimensional analysis was used for pressure drop measurements to generate empirical equations. Furthermore, some equations for calculating shear stresses, regurgitant flow and energy losses are presented.

Chapter Five presents the results and discussions of this study. Firstly, pressure drop data are analysed and discussed, two empirical equations are established for valve design and comparison. The effects of the orifice area, orifice shape and position on pressure drops, velocity and shear stress fields are analysed and established.

Furthermore, a valve prototype called the Jellyfish valve is investigated to establish the effects of the occluder type on pressure drops, velocity and shear stress fields. The effects of the occluder oscillation and the presence of the struts on pressure drops, velocity and shear stress fields are also established.

The conclusion, recommendations and clinical significance of this study for further heart valve design and investigation in terms of fluid dynamics are given in Chapter Six. The verification of experimental techniques is also presented in this chapter to validate the results of this study. The last two sections contain appendixes and a reference list. In the first appendix, the index-matching box, test section and orifice designs are shown. Papers published by the author are attached in *Appendix 2*. Results with raw and analysed data such as pressure drops and LDA velocity measurements across orifices are attached in *Appendixes 3* and *4*.

2.1 Introduction

This chapter will go through the main aspects of prosthetic heart valves. Firstly, the history of valve surgery and replacement is presented with the development of prosthetic heart valves. It looks at the description of different heart valves, especially commonly used heart valves. Secondly, pathological complications are discussed which are directly related to fluid dynamics such as haemolysis, thrombus formation, tissue overgrowth and endothelial damage. A review of orifice flow is necessary, as well as of the valves, since stenotic orifice flow causes problems related to fluid dynamics. This chapter also introduces details and results of the tests and evaluation of prosthetic heart valves with a historical perspective. Furthermore, some criteria for good prosthetic heart valves are presented which all valve designs should exhibit if they are to yield reliable performance and patient safety. Finally, conclusions leading to objectives of this study are presented.

2.2 History of valve surgery and replacement

Experimental cardiac transplantations were carried out in animals from the beginning of this century. In 1905, the first cardiac transplant was performed by Carrell and Guthrie, in dogs, at the University of Chicago. The best survival period for a dog was two hours. Along with others, Mann in 1933 and Demikhove in 1956 carried out their experiments in animals and reported survival durations were 8 and 32 days, respectively. Much later, in 1980, Reitz and Shumway reported their experiments in monkeys with 311 day survival (Lansman *et al.* 1990).

The first clinical surgery was successfully performed by Souttar in 1925 who used his finger to dilate a stenotic mitral valve, this practice continued until 1959 when the transventricular dilator was introduced (Mazumdar 1992).

In 1953 the first prosthetic heart valve (the caged ball type) located in the descending aorta of patients was implanted by Hufnagel (Hufnagel *et al.* 1954) without the use of a heart - lung machine. Unfortunately, this surgery was not successful because the valve was not able to prevent regurgitant flow from the aorta and was also prone to a high incidence of thrombus formation.

In 1960, the first prosthetic heart valve was successfully implanted in humans by Starr and Edwards using the caged ball valve in the position of the mitral valve (Starr and Edwards 1961). Since then, heart valve surgery and prosthetic heart valve implantation have become common clinical practice in medical centres throughout the world.

2.3 Prosthetic heart valves

Prosthetic heart valves were introduced in the early 1950s; the caged ball type was the first to be designed. In the late 1950s and early 1960s, Hufnagel, Bahnson, McGoon, Kay, Muller and many others developed new valve designs with the occluder of flexible leaflets for implantation within the heart, but clinical use of these valves was limited (Harken et al. 1960 and 1962). Tissue fabricated valves have also been introduced, which aim to duplicate the flow behaviour of natural valves. These valves are good for short term use, but for long term are not satisfactory due to the valve failure through calcification, leaflet degeneration, material fatigue, structural deterioration and eventual valve stenosis. However, this valve type (eg. pericardial and porcine tissue heart valves) are closer to the natural form and show advantages over mechanical heart valves in that patients with tissue valve do not need to use anticoagulant therapy (Chandran et al. 1984; Bortolotti et al. 1987; Reul et al. 1990; Purinya et al. 1993 and Chew et al. 1993). The calcification of the valves may be eventually solved by biological and chemical intervention (Pathak et al. 1990). Mechanical failure of the valves may be reduced by modification of the stent and cusp geometries (Krucinski et al. 1992).

Because of the problems associated with the material of the flexible leaflets used as valve occluders, Starr and Edwards developed prosthetic heart valves with rigid components, returning to the caged ball principle. However, the caged ball showed a disadvantage as its central occluder requires a lot of space which leads to anatomical complications in some recipients (Thalassoudis 1987). In an attempt to overcome the problems of the ball valve (eg. improve haemodynamics and reduce weight), the caged disc valve was introduced in 1965 (Hufnagel and Conrad 1965) but this valve type proved the most obstructive of all prosthetic valves. The problems were associated with the occluder of the valve, consequently a new valve design, the tilting disc valve, was introduced and several developments of this type have been made since most of them showing improvements.

In 1977 St. Jude Medical Inc. introduced a bileaflet pivoting valve which consists of two similarly sized semicircular leaflet occluders: it exhibited the least obstructive flow (Hanle *et al.* 1989). This valve type has become very successful and there are numerous references to it in the literature. All the mechanical heart valve prostheses are more durable and their performance is more predictable than bioprosthetic valves. However, the flow patterns produced by mechanical heart valves is an unnatural form, thus they are more prone to thrombosis and patients usually require long-term anticoagulant therapy (Chew *et al.* 1993).

Since 1960, about 50 different cardiac valves have been introduced, many of them have been discarded due to lack of clinical success. The most commonly used basic types of prosthetic valves at present are: (1) caged ball; (2) tilting disc; (3) bileaflet pivoting disk, and (4) tissue bioprosthesis (Hanle *et al.* 1989). A typical mechanical prosthesis consists of four basic components: (1) occluder; (2a) cage, (2b) strut or (2c) hinge; (3) sewing ring, and orifice ring (see *Figure 2-1*).



Figure 2-1 The most commonly used basic types of heart valve prostheses

The occluder, with the orifice ring, takes the role within the heart of allow forward flow when the valve is open and prevent substantial backflow when the valve is closed. The cage, strut, or hinge retains and guides the motion of the occluder in a fixed condition. The cage, strut or hinge and sewing ring are attached to the orifice ring in which the occluder moves under action of blood flow. Blood flows through the orifice when the valve opens and is sealed by the occluder in conjunction with the orifice ring, when the valve closes. The presence of these elements such as the sewing and orifice rings cause a stenosed section and leads to higher pressure gradients across the prosthesis. Having such a ring also induces larger blood shear stresses which will increase haemolytic potential. The presence of the occluder causes jet issue especially in mechanical valves, impingement, stagnation and eddy regions will occur which promote thrombus formation and tissue overgrowth (Tansley 1988). As can be seen from the literature, all artificial heart valves show drawbacks related to fluid dynamics. These drawbacks depend on the structure and geometry of the valves (Hanle *et al.* 1989). For example, caged ball heart valves show high pressure drops, high shear stresses and a large stagnation region in the near vicinity downstream of the heart valve. Because the ball occludes the central flow region it causes a small orifice area. The occluder is relatively heavy so that it causes high pressure drops and energy loss. Furthermore, the ball causes a large stagnation and recirculation region which leads to a large ratio of maximum velocity to average velocity (ie. high velocity gradients) and correspondingly high shear stresses (Hanle *et al.* 1989).

The tilting disc heart valves have two regions of unequal area available for forward flow viz the major and minor flow orifices. These cause very eccentric velocity profiles in the near vicinity downstream from the valve, which generates a large wake behind the disc occluder and causes high velocity gradients. These imply that high shear stresses and pressure drops are produced in the near vicinity downstream of the valve (Hanle *et al.* 1989). The flow performance of the tilting disc valves is considerably worse than that of caged ball valves, on an equal orifice basis (Gentle 1977). Furthermore, because of the eccentric flow downstream of the valve, the extent of the turbulent phenomena depend on the orientation of the valve, as a result, this valve should be orientated during implantation (Chandran *et al.* 1984).

On the other hand, St. Jude bileaflet valves have two similar semicircular leaflets, when it opens the leaflets rotate out to an angle of 85° leaving an orifice that is 85-90% free from obstruction to flow. These leaflets divide the base ring orifice of the valve into three regions. Two of these regions are themselves roughly semicircular in shape and represent about 80% of the area available for forward flow, the third region is located in the centre. This valve induces minimal occlusion, small velocity gradients and symmetrical velocity profiles and leads to small pressure drops and shear stresses (Hanle *et al.* 1989).

The occluders of the three above-mentioned heart valves are different and generate different flow patterns. The tilting disc heart valves generate the highest mean and fluctuating velocity gradients and also generate the highest shear stresses. These are attributed to the considerable eccentricity of the forward flow generated by the tilting disc. The ball occluder produces a large central obstruction leading to small orifice flow, large pressure drops and high wall shear stresses. Whereas bileaflet occluders have some advantages over other two occluder types - such as minimal obstruction leading to large orifice area, low pressure drops and shear stresses and near axial flow patterns.

2.4 Pathological complication

Though heart valve prostheses have been used for several decades, the problems associated with these prostheses have not been totally eliminated. The most serious problems and complications associated with heart valve prostheses are: (a) thromboembolism; (b) tissue overgrowth; (c) infection; (d) tearing of sewing sutures; (e) red cell destruction; (f) valve failure due to material fatigue or chemical change; (g) damage to the endothelial tissue; (h) large pressure gradient across the valve, and (i) leaks caused by failure of the valve to close properly. Problems (a), (b), (e), (g), and (h) are directly related to the fluid dynamics (Woo *et al.*, 1983) and will be discussed in detail in the next sub-sections.

2.4.1 Haemolysis

Haemolysis is red blood cell damage due to mechanical forces acting within the fluid. Blood cells in a region where shear stresses are elevated within the surrounding fluid will experience a distribution of shear stress over their entire membrane. Consequently, the blood-cell membrane will be stretched and may suffer irrevocable changes harmful to its essential function. Sub-haemolytic injury, or damage to blood cells occurs commonly in prosthetic valve recipients. Haemolysis occurs due to disturbance of the valve causing high shear stresses.

Shear stresses are used to indicate the propensity of a valve to damage the blood (Hanle *et al.* 1989; Woo *et al.* 1983 and Tiederman *et al.* 1986). *Table 2-1* shows the effects of shear stresses on blood cells and endothelium by experimental observations of several investigators.

Estimates for shear induced in-bulk haemolysis threshold values have varied widely, from 150 to 4000 Pa (Leverett *et al.* 1972 and Tansley *et al.* 1988). Leverett *et al.* in 1972 considered shear stress and exposure time to be the two primary determinants for in-bulk haemolysis. Blood trauma does not occur when blood is exposed for a very short duration even to very high stresses; but exposure for a long duration with much lower stress levels can cause lysis. Furthermore, blood trauma can occur at values as low as 150 Pa in heart valves as flight-time through valves allows sufficient exposure to take cells beyond their lysis threshold (Leverett *et al.* 1972 and Tansley *et al.* 1988).

shear stress	Result
40 Pa	Damage to endothelial cells (Fry 1968)
90 Pa	Erosion of endothelial cells (Fry 1968)
150 - 4 000 Pa	Damage to red blood cells (Leverett <i>et al.</i> 1972; Hellums and Brown 1977; Lutz and Barras 1983 and Tansley <i>et al.</i> 1988)

Table 2-1. The effects of shear stresses on blood cells and endothelium

2.4.2.Thrombosis

Thrombosis is defined as the formation of a blood coagulum within a vessel or the heart. The presence of prosthetic heart valves in blood flow produce thrombus formation (Yoganathan *et al.* 1981), eg. the downstream side of an occluder type valve, such as caged disk and caged ball, is a region of potential thrombus formation. The low velocity and recirculation regions increase the probability of thrombus formation. The incidence of thrombus formation from prosthetic heart valves, especially from mechanical heart valves represents a major threat to

patients. Consequently, intense anticoagulation therapy is mandatory with any mechanical valve implant (Hanle *et al.* 1989 and Chew *et al.* 1993). High shear stress and turbulence are also triggers of thrombus formation (Huang *et al.* 1994).

The complications that can arise from thrombosis of a prosthetic valve are:

- thrombotic stenosis when a thrombus blocks the prosthesis partially thus inhibits the valve's performance
- thromboembolic events when a part of the thrombus breaks off the main thrombus body and is carried by the blood into the small arteries of a vital organ such as the heart, kidney or brain causing temporary or permanent damage (Mazumdar 1992).

2.4.3 Tissue overgrowth

Yoganathan and his co-workers in 1981 observed tissue overgrowth and thrombus formation on a caged ball valve during autopsy. The presence of cage, strut and sewing ring increases the probability of thrombus formation and tissue overgrowth. Tissue overgrowth occurs due to valve stenosis and high pressure drops across the valve.

Low velocity regions of blood flow generally favour tissue overgrowth. This phenomenon is still not understood, however, high blood flow and the associated effects of blood scouring may play a role in limiting or preventing tissue overgrowth (Thalassoudis 1987). Generally in prosthetic heart valves, the occluder, sewing ring and supplementary elements produce a high disturbance in the blood flow, where separation and recirculation occur. The flow stagnation and low shear stress regions are more prone to thrombus formation and tissue overgrowth than areas of high shear stresses (Yoganathan *et al.* 1981 and Huang *et al.* 1994).

2.4.4 Endothelial damage

The endothelium is the wall membrane of the aorta, blood vessels and body cavities. Endothelial damage occurs due to high wall shear stresses and also increases the potential for thrombus formation (Hanle *et al.* 1989 and Huang *et al.* 1994). Generally, the presence of the orifice ring with the occluder (caged-ball, caged disc or tilting disc) causes a significant increase in velocity gradients in the proximal portions of the aorta. This implies that higher wall shear stress can be observed along the wall of the aorta. In 1968, Fry indicated experimental measurements to determine threshold wall shear stress at which damage and erosion of endothelial cells occurs (see *Table 2-1*).

2.5 Test and evaluation of prosthetic heart valves

Test and evaluation of prosthetic heart valves is one of the most important stages in heart valve design. It assesses the valve's performance and whether or not the valve can be implanted in humans, when the valve is implanted what effects can be attributed to the presence of the valve?

Many researchers have made *in-vitro* measurements of prosthetic heart valves. Firstly, they have judged the fluid mechanical performance of the prosthetic heart valves by measuring the pressure drops and retrograde flow rates across them and by observing the flow pattern around them using flow visualisation. Flow visualisation techniques were applied first to heart valve assessments by Weiting in 1969, Duff in 1970. Following these early investigations, researchers have used visualization techniques to investigate the flow characteristics of valves. These techniques can provide only qualitative information which is useful but not necessary for the comparison of the various designs and modifications of the prosthetic valves (Woo *et al.* 1983). Pressure drop in steady flow is the first indication of acceptability of prosthetic heart valves (Reul *et al.* 1987) and can give an aid for future valve design (Gentle 1977). Therefore, many investigators have focused on pressure drop measurements eg. Forrester et al. (1969); Kaster et al. (1970); Gentle (1977); Yoganathan et al. (1978); Knoch et al. 1988; Hanle et al. (1989) and many others.

In 1978, Yoganathan and his co-workers measured in-vitro velocity profiles and wall shear stresses in the near vicinity of prosthetic aortic heart valves using a Laser Doppler Anemometer (LDA), later the same group (Yoganathan et al. 1979a, 1979b and 1979c) measured and compared the different kinds of aortic prostheses and their modifications (for example, since 1960 the Starr-Edwards valves have had several modifications leading to models: Starr-Edwards 1200; 1260; 2320 and 2400). Chandran et al. (1985a and b) measured turbulent flow phenomena in caged ball and tilting disc valves in pulsatile flow using LDA. Nandy and Tarbell (1988) measured wall shear stress of a trileaflet valve using hot film anemometer. Hanle et al. (1989) compared the most four commonly used heart valve types, especially the effects of the occluder of these valves on velocity and shear stress fields. Teijeira and Mikhail in 1992 investigated flow phenomena of different valves, especially regurgitant flow and energy losses. Other researchers eg. Sergio et al. (1985), Thalassoudis (1987), Tansley (1988), Huang et al. (1994) and many others studied the same parameters using Computational Fluid Dynamics (CFD). These works have focused on:

- Pressure drops high pressure drops favour tissue overgrowth and cause large energy loss which may lead to malfunction of the heart and heart valves. Teijeira and Mikhail (1992) considered pressure gradients to be the most important factor to be considered during the design of a valve.
- Shear stresses high shear stresses cause haemolysis and the threshold level of shear stresses for haemolysis in a free jet is around 400-500 Pa. But blood trauma can occur at a value of 150 Pa when subjected to prolonged exposure (Hellums and Brown 1977; Leverett *et al.* 1972; Lutz and Barras, 1983 and Tansley *et al.* 1988).

- Velocity profiles jets forming downstream of a prosthetic heart valve are deleterious to a valve's proper functioning. Stagnation and separation regions could lead to thrombus formation and tissue overgrowth (Woo *et al.* 1983 and Huang *et al.* 1994).
- Shear rates low shear rates increase thrombus formation and can lead to valve dysfunction or embolism (Tansley 1993).

2.5.1 In-vitro measurements and comparisons of prosthetic heart valves

The comparison of the hydrodynamic *in-vitro* with the *in-vivo* measurements of the normal human valves is very problematical, as it is very difficult to measure *in-vivo* exactly enough for comparison with the *in-vitro* results (Heiliger 1987). However, *in-vitro* measurements and prediction using computational and experimental techniques of flow parameters of different valves can be compared with each other to chose the best valve.

The use of different blood analogue solutions as the medium for *in-vitro* tests could lead to some differences, especially in laminar and low velocity flow regions. However, aspects of non-Newtonian blood flow in prosthetic valve studies and the use of different analogue solutions in the prediction of flow parameters in highly turbulent and complex flow regimes should lead to accurate representations of the *in-vivo* situation (Tansley 1993). As a result, many studies have focused on *in-vitro* measurements using experimental techniques with analogue solutions for the purpose of comparison of different heart valves for pressure drops, velocity and shear stress fields, regurgitant flow and energy losses.

2.5.1.1 Pressure drops

Pressure drops measurements under both steady and pulsatile flow conditions are widely reported in literature. Pressure drops in steady flow were compared for different valves with the same size, whereas pressure drops in pulsatile flow were used for calculating energy losses and mean systolic pressure gradients to correlate steady data. Pressure drop measurement is one of the most important stages in assessing heart valve prostheses. Thus many investigators have focused on this component measurement eg. Forrester *et al.* (1969) measured pressure drops through fifteen different types of aortic prostheses under steady flow condition, Kaster and his co-workers (1970) compared the Lillehei-Kaster pivoting disc aortic valve with four other prosthetic heart valves under pulsatile flow conditions, Yoganathan *et al.* (1979a) measured and compared pressure drops across ten different prosthetic aortic heart valves under both steady and pulsatile flow conditions. Many other researchers have measured pressure drops, eg: Yoganathan *et al.* (1981); Heiliger (1987); Hanle *et al.* (1989).

Pressure drops were also compared to determine the effects of different viscosities on the results eg. pressure drops across ten prosthetic heart valves were measured under both steady and pulsatile flow conditions using two different Newtonian liquids having different viscosities and results showed no differences caused by the use of different liquids as test media (Yoganathan *et al.* 1979a).

Generally, pressure drops were measured and analysed for effective orifice area using the Gorlin and Gorlin (1951) formula and valves were compared for effective orifice area and efficiency index (Chandran *et al.* 1984); Heiliger 1987 and Hanle *et al.* (1989). A more complete comparison could be afforded by applying a constant of linear proportionality between pressure drop and square of flowrate/unit area as suggested by Gentle (1977). He condensed pressure drop versus square of flowrate/unit area (Q^2/d^4) and linear regression revealed a slope. The efficiency of the valves was defined as the ratio of the slope of an ideal orifice to that of the
valves (Gentle 1977). Pressure drops across an ideal orifice are condensed in the following form:

$$\Delta P = 1775 \frac{Q^2}{d^4}$$
 (Equation 2-1)

where Q is flowrate in l/min and

d is the orifice diameter in mm.

In a similar form, condensed pressure drops of any valve types are follows:

$$\Delta P = S \times \frac{Q^2}{d^4} \tag{Equation 2-2}$$

where S is the slope of the ΔP and Q^2/d^4 relationship of the valves.

The hydraulic efficiency *E* of the valves can be written as:

$$E = \frac{1775}{S} \times 100\%.$$
 (Equation 2-3)

As mentioned before, the comparison between *in-vitro* and *in-vivo* results is very difficult. However, the Gentle method can give an ideal not only for the comparison of valve against valve, but also against a theoretical value. This procedure can give an aid for future valve design.

2.5.1.2 Velocity profiles

Low velocity and recirculation flow regions increase the probability of thrombus formation (Figliola and Mueller 1981), stagnation and separation regions could lead to thrombus formation and tissue overgrowth and jets forming downstream of a prosthetic heart valve are deleterious to a valve's proper functioning (Woo *et al.* 1983). High velocity gradients imply high shear stresses (Hanle *et al* 1989). Furthermore, shear stress measurements stem from velocity measurements as velocities can be divided into two components, mean and fluctuating; two orthogonal fluctuating components are used for calculating turbulent shear stresses

which cause effect on blood cell. The mean velocities are plotted to determine the stagnation and recirculation regions which promote thrombus formation and tissue overgrowth and may lead to dysfunction of the valves. This need for heamodynamic information has lead to velocity profiles in heart valve prostheses being investigated extensively and comparisons made with similar studies.

Velocities of flow through heart valve prostheses have been measured under both steady and pulsatile flow conditions and generally using hot-wire anemometry and LDA techniques. Yoganathan et al. (1981) compared velocity profiles of the Starr-Edwards aortic ball valve with the ball occluder tied and untied using LDA and found that the oscillation of the occluder reduced the extent of the stagnation and recirculation region, however, shear stress and pressure drops were increased. This region could encourage thrombus formation and tissue overgrowth on the apex of the cage and along struts of the ball valve. Hasenkan et al. (1988) compared velocity fields downstream of six mechanical aortic valves in a pulsatile flow model using a hot-film anemometer probe. Hanle et al. (1989) measured and compared velocity profiles of four valve types using LDA. These valves had the same orifice diameter, but different occluders so that they had different effective orifice areas. The tilting disc valve generated very high mean velocity gradients because of the considerable eccentricity of the forward flow generated by the tilting disc. Whereas the St. Jude Medical bileaflet valve produced the lowest mean velocity gradients due to having the highest effective orifice area and concentric forward flow. On the other hand, bioprosthetic valves generated the highest velocity gradients due to the triangular shape of the valve when the valve was fully open (see Table 2-2).

2.5.1.3 Shear stresses

The presence of a prosthetic heart valve in blood flow produces disturbances and high shear stresses which lead to blood trauma in valve recipients. Therefore, many studies in literature have focused on shear stress measurements. Yoganathan (1979a) measured *in-vitro* velocities in the near vicinity of the Björk-Shiley aortic

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prosthesis using LDA. The Reynolds shear stresses were calculated from u' and v', the axial and tangential fluctuating components, respectively. The maximum shear stress was estimated to be 100 Pa. Later, the same group (Yoganathan *et al*·1979b and c) made measurements of the Starr-Edwards aortic ball valve and reported a maximum shear stress of 175 Pa from u and v components.

Woo *et al.* in 1983 investigated *in-vitro* fluid dynamic characteristics of the Abiomed trileaflet heart valves (Number 25 and 21 valves) and reported maximum shear stresses of 220 and 450 Pa in the immediate vicinity of the number 25 and 21 valves, respectively. These values exceed the threshold shear stress value of 150 Pa for blood trauma.

In 1985 Walburn and Stein measured flow parameters in a Hancock porcine bioprosthetic aortic valve under pulsatile flow condition, the instantaneous shear stresses were calculated from u'_1 and u'_2 components where u'_1 and u'_2 are the fluctuating velocities measured at $\pm 45^{\circ}$ relative to the direction of the mean flow in the horizontal plane; in other words, shear stresses are calculated from u' and w' components, axial and radial, respectively. They reported a maximum shear stress of 254 Pa.

Hanle and his co-workers in 1989 measured and compared four different types of prosthetic valves such as the Björk-Shiley (tilting disc valve), Smeloff-Cutter (double-caged ball valve), St. Jude Medical (bileaflet valve) and Ionescu-Shiley (bioprosthesis). They reported the bileaflet valve having smallest turbulent shear stress of 76 Pa and bioprosthesis valve having highest shear stress of 128 Pa in comparison with those of other three valves (see *Table 2-2*).

2.5.1.4 Backflow and energy losses

Backflow occurs during the closing and closed phase of the valves' cycle. Leakage gaps may lead to increased haemolysis because of higher shear stresses within the

gap flow and within the turbulent mixing region of the backflow jet. The leakage jet velocities are about 3 to 5 times higher than the peak velocities during systole (Knott *et al.* 1988). For example, the tilting valves exhibit 3 leakage jets which correspond to the one central and two peripheral gaps. No such leakage jets were observed with the ball valves since, in the closed position, there are no gaps between the silastic ball and the housing rim. Woo *et al.* (1983) measured regurgitant flow and energy losses of two Abiomed valves (size number 21 and 25) and reported regurgitant flow of 0.7% and 2.8% of total cardiac output. These values are small in comparison with 8.4% and 14% of the Björk-Shiley and St. Jude Medical mechanical valves, respectively.

Energy loss is the product of flowrate and pressure drop, and occurs in three distinct stages. For example, in the aortic position, these three energy losses are: (a) resistance of forward flow during systole; (b) reverse flow during closing and (c) leakage flow during the closed phase (Teijeira and Mikhail 1992). Knott and his co-workers (1988) considered leakage flow and energy loss to be the most serious source of cell damage and thrombus formation. *In-vitro* energy losses indicate that as much as 10% of the ventricular energy can be lost by each mechanical prosthesis. Energy losses in the first stage by mechanical heart valve prostheses is always larger than those in other two stages and ranks from 40 to 60% of total energy losses (Teijeira and Mikhail 1992).

2.6 Review of orifice flow

The orifice is one of the oldest known devices for measuring and regulating the flow of fluids, chiefly water. It is known that when fluid flows through an orifice a pressure gradient can be observed, this pressure drop is proportional to the velocity of the flow or flowrate through the orifice. This effect is used for measuring fluid flow by devices known as an orifice meter.

Flow is measured by recording pressure drops across the orifice as the presence of the orifice in the flow causes pressure gradients between up and downstream of the orifice. *Figure 2-2* shows static pressure distribution along a tube into which an orifice is installed. Close to the inlet of the orifice, the static pressure in the pipe increases slightly and reaches its maximum value at the entrance to the orifice. The pressure of fluid drops abruptly as it flows through the orifice and, on the outlet side, the pressure continues to decrease.



Figure 2-2. Static pressure distribution through an orifice

The minimum value of static pressure is reached at a short distance from the outlet side of the orifice. Beyond this minimum point the static pressure increases again, at first slowly, then rapidly and reaches the second point of maximum value several diameters downstream of the orifice plate, this phenomenon is referred to as pressure recovery. Consequently, ΔP_0 is the overall pressure loss, which is less than the non-recovered pressure drop. This point is called as the point of the maximum pressure restoration. For all the concentric orifices, the point of maximum pressure restoration occurs at a distance of 4 pipe diameters downstream of the orifice, and for the special orifices eg. eccentric and segmental, the maximum restoration of the pressure occurs at the distance of no less than 5 pipe diameters from the plane of the orifice (Horace *et al.* 1916).

Pressure gradients through orifices strongly depend on the orifice-to-pipe diameter ratio and flowrate (Gerhart and Gross 1985). The more the diameter ratio increases, the less pressure gradient can be observed. However, for the same diameter ratio but for different orifice types such as the Venturi tube; the concentric thin-plate orifice, and the eccentric and segmental orifice the pressure drop exhibits different values. The overall pressure loss through the eccentric orifice is largest and the pressure drop through the thin-plate orifice is somewhat larger than through the Venturi tube (ASME 1959). This may mean that the eccentric and segmental orifice causes more disturbance in the flow downstream of the orifice than the concentric orifice does. Furthermore, pressure drops depend on the roughness of the orifice and the tube surface (Clark, 1965). The flow régime upstream of the orifice (eg with or without straightener, the position of the straightener and elbow in the test configuration), and the position of the orifice installed in the pipe also caused effects on flow measurements (ASME 1935, Scott *et al.* 1993, and Scoot and Lewis 1994).

In conclusion, there are many investigators in literature who have studied pressure drops and losses across orifices. None of them have focused on velocity and shear stress fields and the relationship between pressure drops, shear stress and velocity fields in the vicinity downstream of the orifices. Therefore, this study shall investigate the effects of the primary orifices on pressure drops, velocity and shear stress fields in the vicinity downstream of the orifices and to apply these effects on heart valve fluid flow.

2.7 Criteria of a good prosthetic heart valve

In order to allow a prosthetic valve to satisfy long-term effectiveness in clinical application, Henze *et al.* (1973) considered that a good prosthetic valve to must fulfil the following design criteria:

- It must be fabricated of chemically inert materials that are tissue compatible, reasonably atraumatic to blood elements, and nonthrombogenic.
- It must be durable enough to retain physical and geometric properties over many years of usage.
- It must present minimal obstruction to the forward flow of blood in the open position.
- It must open and close quickly in response to alterations in pressure gradient, and be relatively competent in the closed position.
- Its permanent fixation must be technically feasible, safe and secure over many years.
- The valve should not annoy the patient by being noisy and it should not require the patient to modify his or her lifestyle appreciably.

2.8 Conclusion and objectives

Table 2-2 shows Hanle *et al.'s* work from 1989, and as can be seen the occluder plays a very important role in determining flow patterns and flow characteristics of the valve. The ball valve presents the most obstructive area in comparison with those of the three other valve types, it leads to the highest pressure drops, but shear stresses are not the highest.

The tilting disk and tissue valves show the highest shear stresses as the tilting valve produces eccentric flow, whereas tissue valves generate the highest velocity

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gradient due to the triangular shape of the orifice when the valve is fully open. Pivoting disk valves have the largest flow area producing the lowest pressure drops, shear stresses and velocity gradients.

Valve	Effective	Pressure drops	Shear stresses	Velocity gradients
types	area (cm ²)	(kPa)	(Pa)	(m/s)
Ball	2.17	Highest (2.2)	78	Lowest (1.2)
Tissue	2.57	1.3	Highest (128)	Highest (2.4)
Tilting	2.71	1.4	112	1.6 and low region
Pivoting	3.00	Lowest (1.0)	Lowest (76)	1.4

Table 2-2. Dependence of flow phenomena on flow configuration. From Hanle et al (1989)

In conclusion, orifice area can reduce dramatically the flow turbulent phenomena such as pressure drop, velocity gradient and shear stress. Furthermore, the orifice shape and position are important factors in reducing such effects on blood flow through valves. Pressure gradient does give enough information about shear stress. Eccentric flow and high velocity gradient imply high shear stress which are unaccounted for (or not predicted) by pressure gradient. In terms of orifice flow, the effects of several factors such as diameter ratio; roughness of the orifice surface; upstream régime and structure; and orifice types on pressure drop and flow measurements were investigated carefully. However, none of the orifice studies have focused on velocity and shear stress fields and the relationship between pressure drops, shear stress and velocity fields in the vicinity downstream of the orifices.

2.9 Directions for this study

The above discussion lends direction to this study, which focuses on two major topics:

- Investigation of the effects of the orifice area, shape and position; and occluder position on fluid dynamics of the valves by measuring velocity profiles and pressure drops across different orifices.
- Investigation of a newly designed valve called the Jellyfish valve, to establish the effects of the occluder on pressure drops, velocity and shear stress fields (the Jellyfish valve has a special occluder which is a flexible membrane attached to the centre of the orifice ring).

This chapter deals with two major themes: firstly, different techniques which may be used for investigating heart valve flow, are reviewed to select suitable techniques for this study; and secondly, instruments and experimental set-ups which were used as major techniques in this study are described.

3.1 **Review of possible techniques**

The success of a given prosthetic heart valve design is based on many criteria. One important set of criteria is the fluid mechanical characteristics of the valve design. There are many approaches used for solving flow problems in heart valves. These approaches fit into three broad categories: numerical, analytical and experimental; each approach has distinct advantages and unique disadvantages. In the sections which follow, some techniques which may be used for investigating fluid flows in valves are described.

3.1.1 Computational Fluid Dynamics

Numerical and analytical methods are referred to here as Computational Fluid Dynamics. These methods are based on algebraic equations, These methods usually lead to a vast number of finite-difference or finite-element equations which are solved by computer.

The Navier-Stokes equations describing fluid flow are partial differential equations. These equations cannot be solved by analytical methods as these methods can only be applied to simple flow configurations. Such flow situations do not occur in prosthetic heart valve flow. Heart valve flow is either undeveloped-laminar or turbulent (Tansley 1988). As a result, the use of analytical methods in heart valve flow is very restricted.

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Numerical methods offer solutions to differential equations to solve problems in fluid flow of prosthetic heart valves. Detailed understanding of flow characteristics at every point of the flow field in heart valve prostheses can be obtained by numerical simulation (Huang *et al.* 1994). Unfortunately, the standard computational numerical methods are restricted in their ability to solve turbulent fluid flow, especially pulsatile flow because the requirements of excessive storage space and run time make it impractical in existing computers (Tansley 1988). However, CFD can offer some advantages over experimental methods as follows:

- In small space where experimental techniques are impossible to access.
- In real blood and near to the wall or occluder surface where results gained experimentally are influenced.
- A full picture of the flow field in heart valve prostheses can be obtained.
- CFD is relatively cheap and time saving for valve design.

3.1.2 Experimental techniques

An extremely important and (potentially more) reliable approach is experimentation which is able to deal with different flow problems and flows in complicated geometries. However, experimental techniques are not capable of providing a full picture of a flow field, they can only give information where the probe was inserted and measurements taken. Due to the limitation of experimental apparatus and the structure of prosthetic heart valves, it is very difficult to experimentally measure flow parameters in the immediate vicinity of the valves (Huang *et al.* 1994). Nevertheless, experimental methods are usually used as a tool for assessing heart valve flow; sufficient care is needed so that results are valid and that measurement processes do not unduly affect the fluid mechanics being observed. Experimental methods also find application in verifying computational methods; the two different approaches are complimentary with CFD filling in gaps in measured data and experimental results verifying correctness of computational models.

Since prosthetic heart valves have been used clinically, many investigators have investigated the fluid mechanical performance of valves. Firstly, flow visualisation technique was applied for observing the flow patterns around valves. Pressure drop and retrograde flowrate measurements across valves have been carried out since the late 1960s. These techniques were good but not able to provide all of the necessary information for comparison of various valve designs (Yoganathan *et al.* 1978). Consequently, since the 1970s many fluid dynamical measuring techniques have been adapted to measuring velocities and determining shear stress fields in the near vicinity of prosthetic valves eg. hot-wire anemometers or hot-film anemometers (Figliola 1976); Laser Doppler Anemometers (LDA) (Wang 1977 and Yoganathan. 1978) and Doppler ultrasound anemometers (Jorgensen *et al.* 1973). All of these techniques are still used to investigate fluid flow in heart valves. In order to elaborate further, some experimental techniques are discussed, in the following sections, for their limitations and capabilities.

3.1.2.1 Flow visualisation

Patterns of fluid flow in heart valves can be observed using flow visualisation techniques, eg streaklines, wherein small tracer particles such as powders, emulsions, gas bubbles or beads are seeded into the flow. As these tracers pass through an illuminated section the paths they prescribe are recorded by photographic film or video. Flow visualisation experiments in Woo *et al.* (1983) were performed to provide a good qualitative description of the flow field of heart valve prostheses. Moreover, by, observing the whole flow field of the valve it was possible to decide where to conduct the detailed quantitative LDA measurements. However, the flow visualisation technique can provide only qualitative information of the flow. This information is very useful but not good enough for comparison of flows of various valves (Yoganathan *et al.* 1978 and Yoganathan *et al.* 1979c). Many flow

visualisation techniques are applicable to the assessment of heart valve flow and the reader is referred to JSME, 1988 for more details.

3.1.2.2 Pressure drop measurements

Pressure tappings are made in the side of the test section wall, one upstream and one or more downstream of the valve. Pressure measuring devices such as U-tube and pressure transducers are connected to the taps to measure directly either pressure difference across the valve or gauge pressure above atmospheric, then pressure drops across the valve are calculated from the difference between upstream and downstream static pressures. In this study, piezoresistive strain-gauge transducers were used for measuring up and downstream static pressures. Energy loss measurements are calculated as the product of pressure drop and flowrate measurements.

Pressure drop measurements are still used as the definitive classifier of the valve haemodynamic performance. These techniques are very cheap and simple to apply for static pressure gradient and pressure recovery information. However, pressure drop measurements alone are not enough for providing information about haemolysis, thrombus formation and tissue overgrowth caused by the presence of the valve in the flow. Thus, velocity measurement techniques were introduced to produce more information of the valve haemodynamic performance.

3.1.2.3 Velocity measurements

The major techniques commonly used for velocity measurements in the literature are: Pitot-static tube; thermal (hot-film and hot-wire) anemometry; Laser Doppler Anemometry (LDA) and Ultrasound Doppler. These are briefly discussed below.

3.1.2.3.1 Pitot Static Tube

The Pitot tube is the most traditional velocity measuring instrument, its mode of operation is based on Bernoulli's equation:

$$P_{t} = P_{t} + P_{d} = P_{s} + \rho \frac{U^{2}}{2}$$
(Equation 3-1)

where P_t : is total pressure

 P_s is static pressure

 P_d is dynamic pressure

 ρ is the density of the flow medium

U is the (axial mean) velocity to be assessed.

Static and total pressures are obtained by a probe called a Pitot-static tube, which is placed into the flow field. Static and dynamic pressures are gained by nozzles 1 and 2, respectively (see *Figure 3-1*). The difference between these two pressures is proportional to $\frac{1}{2} \rho U^2$.

When a Pitot-static tube is used for measuring velocities, some conditions must be considered such as: (a) the tube should be aligned within about $\pm 10^{\circ}$ of the flow direction; (b) the root mean square intensity of turbulence in the stream should be smaller than 5% of the mean velocity; (c) the total pressure does not change more than 1 to 2% across the tube diameter; (d) the probe is not too near to the wall, (d) the probe size is not so large as to interfere with the flow velocity significantly (Bradshaw 1975).

Velocity fluctuations cannot be measured with a Pitot-static tube, but Pitot-static tubes are generally used as calibration references because the accuracy of these measurements is about 0.25% and higher than other techniques eg. hot-wire and LDA.



Figure 3-1. Pitot static tube

3.1.2.3.2 Hot-wire or hot-film anemometers

Hot-wire or hot-film anemometers rely on a heated body. The temperature of a heated body in a flow depends on the velocity of the flow into which the heated body is inserted, so that velocity can be measured by calibrating in terms of temperature. Early hot-wire probes suffered the disadvantages that they could not be used in liquid or in fact in any flow environments more hostile than a standard laboratory wind tunnel. This problem has now overcome by the introduction of coated probes or hot-film probes (Lomas 1986).

Figure 3-2 shows a typical hot-wire probe. It consists of a wire sensor whose ends are welded onto the tips of two support needles. These two support needles are supported by the probe body. The wire sensor is usually made of Tungsten or Platinum, about 1 mm long (l) and 5 μ m in diameter (d). Generally, the ratio of l to d is between 200 and 400. The diameter is limited by the need for an adequate electrical resistance and by the need for the wire to respond to rapid fluctuations in heat transfer due to changes in velocity.

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The sensors of hot-film probes are usually made of Nickel or Platinum deposited in a thin layer onto a backing material, such as Quartz, and connected to the electronics package by leads attached to the ends of the film. A thin protective coating of Quartz is deposited over the film to prevent damage by chemical reaction.

There are three types of electronics packages (Lomas 1986) which are used to control the sensor heating current in different modes. Firstly, the most common is the constant temperature anemometer which supplies a heating current that varies with the fluid velocity to maintain constant sensor resistance, thus constant sensor temperature. Secondly, and less often used, is the constant current anemometer which supplies a constant heating current to the sensor, this type has the disadvantage of suffering from thermal inertia. The third type is the pulsed wire anemometer which measures velocity by momentarily heating a wire to heat the fluid around it.



Figure 3-2. Typical hot wire probe

Hot-wire or hot-film anemometry can be used for measuring not only the velocity, but also the direction of the flow and fluctuations. This technique is very well established, widely accepted and relatively cheap to install. It is a simple technique and can be used in opaque media. The technique will yield velocity and Reynolds shear stresses and wall shear stresses. However, there are some disadvantages such as the sensor is sensitive to dust in air and slime in liquid, so that frequent recalibration is necessary; and the probe insertion complicates the test section geometry. Furthermore, the probe insertion into the flow channel perturbs the flow and may lead to erroneous results.

3.1.2.3.3 Laser Doppler Anemometer (LDA)

Laser Doppler anemometry is based on the Doppler effect; which is caused by moving the source of the light or the receiver. This effect can be used for measuring particle velocity. When a particle moves and passes through the light, it represents the moving receiver and causes the Doppler effect. This Doppler effect is detected and analysed to calculate the particle velocity.

LDA relies on the scattering of light by microscopic particles in the fluid flow. The most popular LDA system uses the two beam correlation method. Two laser beams cross and cause an intersection and fringes (see *Figure 3-5*). As a particle moves through the region of interference fringes it will scatter light, whose intensity will vary according to the light intensity variations inside the bisector of the two beams. The returned signal contains a varying amplitude superimposed on to a high frequency signal, the frequency of which is inversely proportional to the velocity of the particle These light intensity variations are detected by a photodetector and processed by signal processing system.

Figure 3-3 and Figure 3-4 show two typical optical configurations and their basic components in back- and forward-scatter mode, respectively. An LDA system, in back- or forward-scatter mode, always consists of five main components: a laser source; beam-splitter; frequency shifter; photodetector; and signal processor. A beam from the laser source passes through the beam-splitter to become two beams which then cross each other to make the intersection in the flow channel (the measurement volume). A frequency shifting system is mounted next to the beam-splitter and is used to: reduce the percentage of frequency change in highly turbulent

flows; optimize frequency, reduce fringe bias and increase the accuracy of measurements. The frequency shift system is designed to increase the application range of LDA by shifting the frequency of the laser light; this permits the measurement of: reversing flows; low velocity convective flows; vortex and recirculation flows; pulsatile flows; and velocity components perpendicular to the mean flow direction. This system consists of two separate components, namely the an acousto-optic cell (called a Bragg cell) and a downmix circuit (TSI incorporated 1986).

The last two components are the photodetector and signal processor. Two types of detectors are commonly used, photodiodes and photomultipliers. For high light level and small band width laser sources, photodiode detectors are the most satisfactory. Photodiodes have the advantage of being small in size and relatively inexpensive; they do not require any high-voltage power supply as do photomultiplier tubes and are usually used under daylight conditions without any optical screening. At low light levels and wide band width in high speed-flow measuring situations, photomultipliers are superior (Durrani and Greated 1977). The photodetector's function is that of collecting Doppler signals to the signal processor where the signals are filtered, amplified and processed to calculate mean velocities, turbulence intensities and shear stresses.



Figure 3-3. Typical back scatter mode optical configuration and basic components



Figure 3-4. Typical forward scatter mode optical configuration and basic components

There are two basic types of signal processors: counters and Burst Spectrum Analysers (BSA). Counter-type signal processors work by counting the number of cycles in a fixed time or measuring time at a preselected number of cycles. BSA is a simple method of analysing signals from LDA systems, at which Doppler signals are analysed by direct spectral analysis (Durrani and Greated 1977).



Figure 3-5. Two beam intersection

LDA has many advantages over other techniques, however, accurate flow measurements strongly depend on the following conditions: particle concentration

and size in the fluid; quality of optical systems; the sensitivity of photodetectors; the signal processor; and the alignment of the optics (TSI incorporated 1985).

In order to get accurate flow measurements with LDA, the conditions of particles in the fluid are as follows:

- The particle is spherical and small in size compared with the smallest wavelength of the fluid motion.
- The pathlines of the particle and fluid coincide, no over-shooting takes place.
- The flow is not perturbed by the presence of the particle (Durrani and Greated 1977).

LDA can be used for measuring velocities, shear stresses and turbulence intensities in both steady and pulsatile flow conditions. Furthermore, these measurements can be established in three dimensions in coincidence windows. However, LDA cannot easily be used to measure fluid velocities in opaque media (Stern 1985). Distortion of the control volume by refractive index mismatching can occur leading to either measuring in the wrong place or false results.

LDA can be used for measuring fluid velocities in opaque media eg. blood flow by introducing the self-mixing effect technique (Slot *et al.* 1992 and Mito *et al.* 1993). Like ultrasound Doppler, fibre-optic LDA using the self-mixing effect technique can be used for *in-vivo* measurements due to the small size of fibres. LDA has a high spatial resolution in comparison with other techniques eg. ultrasound Doppler. However, one of the shortcomings of this technique when measuring in blood flow, is the fact that LDA using the self-mixing effect measures invasively, whereas for example ultrasound Doppler anemometers can measure noninsavely (Slot *et al.* 1992).

Like LDA, this technique relies on the Doppler principle, as particles pass through the reference beam a Doppler shift is created in the reflected beam. The magnitude of the shift is proportional to the velocity of the particles. Unlike LDA, the beam is of ultrasound waves. This technique can be used for yielding information about heart valve flow *in-vivo*. However, a major disadvantage of ultrasound Doppler method compared to the other techniques is poor spatial resolution, because the size of the control volume yielded by ultrasound Doppler is very large, consequently, the results are very noisy and inaccurate; and due to a lot of the smaller scale turbulence information, velocity profiles cannot be accurately assessed (Hughes and How 1994).

In conclusion, the LDA technique offers many advantages over other techniques: (a) it requires no probes to be inserted into the flow channel; (b) requires no calibration whatsoever; (c) has a high signal/noise ratio and therefore can be used with good accuracy to measure velocities in highly disturbed flow fields like in heart valve flow; (d) can be used with good accuracy to measure velocities close to prosthetic valves and to the walls of flow channel; (e) has a high frequency response (at least 10^5 Hz); (f) can distinguish between forward and reverse flow directions (Yoganathan *et al.* 1979b) and (g) Reynolds stresses can be obtained through the use of coincidence of two orthogonal velocity component measurements. Like other techniques, such as hot-film anemometry and ultrasound Doppler anemometry, LDA using the self-mixing effect can be used for measuring blood flow both *in-vitro* and as well *in-vivo*.

3.1.2.4 Flow metering

Flowrate through prosthetic heart valves is measured under both steady and pulsatile flow conditions. There are three popular flow meter types applied to prosthetic heart valve flow measurements, these are floating, turbine and electro-magnetic flow meters. Floating and turbine meters are suitable for measuring steady flow, whereas electro-magnetic meters are suitable for measuring in both steady and pulsatile flows.

The floating meter (Rotameter) is the most basic flow meter type consisting of a body, which is floated in a conical tube at a level proportional to the flowrate through the tube. The turbine flow meter relies on the movement of a turbine inserted into the flow. This movement is proportional to flowrate through the turbine which is then converted into flowrate electrically or mechanically. The electro-magnetic meter works by the Hall effect where an electrically conducting fluid, passing through a field of magnetic flux, generates an EMF proportional to flowrate through the meter.

3.1.3 Summary of measurement techniques

After viewing the different approaches for solving fluid flow problems, experimental methods seem to be the most suitable for prosthetic heart valve flow; as the flow through heart valve prostheses is complicated and the geometry is not simple for modeling and solving flow problems using CFD. Therefore, this study was carried out using experimental techniques such as LDA for measuring velocities, shear stresses and turbulence intensity; pressure taps and flow meters for measuring pressure losses, flowrate and energy losses.

3.2 Experimental set-up and instrumentation

In the next sections, some experimental set-ups and instruments used in this study are presented. Laser Doppler anemometry, pressure transduction and flow meters were used as the major research tools throughout this study. Steady flow generated by two small centrifugal pumps circulated through artificial valve and orifices and was returned, via a floating flow meter to an open sump. Flow was also straightened by a flow straightener installed at about 30 tube diameters upstream of valve or orifice location, so that the flow before entering the valve or orifice was fully developed, turbulent tube flow (see *Figure 3-6*). Valves and orifices were inserted into a plain acrylic tube of internal diameter of 19 mm which was placed in the refractive index matching box (*see Figure 3-8*, or for more detail see *Appendix 1*). A blood analogue fluid of water-saline solution was used in all the *in-vitro* experiments.



Figure 3-6. Schematic of steady flow measurement

In order to reduce the error in pressure drop measurements, static pressures were kept as low as possible, because pressure drops were calculated from the difference between the two static pressures in upstream and downstream regions and each static pressure was measured above atmospheric pressure (see *sub-section 3.2.4*). Thus,

two small pumps were installed in parallel to increase flowrate up to $500 \times 10^{-6} \text{ m}^3/\text{s}$ (30 l/min)and maximum static pressure of around 16 kPa (120 mm Hg). Steady flow measurements such as pressure drops were made at flowrates of between 100 and $417 \times 10^{-6} \text{ m}^3/\text{s}$ (6 to 25 l/min), whereas velocities were carried out at only one constant flowrate of $417 \times 10^{-6} \text{ m}^3/\text{s}$.

3.2.2 Pulsatile flow circulatory system

Pulsatile measurements were conducted through the Jellyfish valve (no pulsatile measurements were made through the orifices) in a mock loop based on the vi-vitro system (Leefe et al. 1986) with an in-house fabricated ventricle (heart duplicator) and flow elements. The pulse duplicator and mock loop were used for generating pulsatile flow for cyclic flow tests. This duplicated heart outflow allowed for the control of variables such as cardiac output, aortic pressure and heart beat rate. The ventricle consisted of a chamber and in its inlet a prosthetic heart valve was installed. Blood analogue was contained inside the ventricle chamber separated from the piston pump by a polymeric membrane. The frequency of the pump could be regulated by a VSI pump frequency controller. The cardiac output was controlled by adjusting the stroke length of the piston inside the cylinder pump; adjusting throttle and aortic pressure. The required aortic pressure was adjusted by relieving air from or pumping air into the compliance chamber or changing the free surface height within this chamber (see Figure 3-7). In order to achieve a required aortic pressure and cardiac output, firstly pump frequency was set, then all adjustable components such as the stroke length; adjusting throttle and compliance chamber settings were regulated in sequence.

Velocities, pressure drops and flowrate in pulsatile flow were measured over eight cycles and then analysed for mean and fluctuating values using a 5° binning analysis (see *section 4.2*). Pulsatile velocities across the valve were measured using an LDA system . Pressure drops were measured using pressure taps (see *sub-section 3.2.4*) and volumetric flow measurements were made in pulsatile flow using an electro-

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magnetic flow meter¹ rigidly attached 250 mm downstream of the valve base ring. All tests were conducted at a heart rate of 1.2 Hz (72 beats/min) with aortic pressure set at 10.26/16 kPa (80/120 mmHg) and a cardiac output of 93.3×10^{-6} m³/s (5.6 l/min). with the Jellyfish valve located in (the in-vitro equivalent of) the aortic position.



Figure 3-7 Heart duplicator and schematic pulsatile flow channel

The 5° binning analysis used is introduced in *section 4.2*. The accuracy of the mean values depended on the number of cycles measured, the size of the bins, and the extent of flow turbulence (Reynolds number). In order to gain a satisfactorily converged mean value (a good average with minimum standard deviation) of each measuring point in cyclic flow, the above parameters such as the number of cycles

¹ Zepeda Instruments (Seattle, Washington) SWF5 Electromagnetic square wave flowmeter of 19 mm diameter

measured and the size of the bins were chosen (see *section 4.2*) using results found from previous studies (Schoephoerster and Chandran 1991; and Jin and Clark 1994). In this study, a bin size of approximately 12 ms (corresponding to 5° of each cycle) and number of measured cycles of 8 were selected giving the convergence of mean data with correlation factor of 98%.

3.2.3 Turbulence phenomena determination using LDA

The laser Doppler anemometers used were two-beam systems operated in the backscatter mode. Two systems were employed, one at The University of Adelaide and the other at The University of Melbourne. The system in Adelaide was used in pulsatile flow tests to determine velocity profiles and shear phenomena in the flow through the Jellyfish valve. The LDA system in Melbourne was used in steady flows through orifices as the major technique of this study to determine flow turbulence phenomena.

The Adelaide's system comprised 488 nm and 514.5 nm beams from a 5 W Spectra Physics 165 argon-Ion laser driving a TSI 9100-7 laser Doppler anemometer. Optics included two Bragg cells, a beam expander (to 82.5 mm beam spacing) and a 450 mm lens mounted on TSI 9400 traverse. Signal processing was achieved by TSI 1990C counters, data to which was phase resolved by interrupting the hand-shaking between the counters and controlling PC by an in-house built device. This hand-shaking interruption allowed for the 5° binning analysis. Unlike the system in Adelaide, the LDA system in Melbourne possesses fibre-optics with a beam intersection half angle of 4.35°. The laser source is a Spectra-Physics Stabilite 2017 Argon-Ion laser. The probe traverse system in Melbourne is fully automatic, this reduced the time needed to measure one data set from three days (measured manually in Adelaide) to a maximum of four hours. The LDA seeding particles used were 11 μ m metallic coated spheres and the signal processor used was a Burst Spectrum Analyser (BSA).

Artificial heart valves and orifices were inserted into a plain acrylic tube (refractive index 1.48 and internal and external diameter of 19 and 25 mm, respectively) which was then placed in an index matching box (see *Appendix 1* and *Figure 3-8*) filled with medical grade paraffin to reduce refraction. Index matching was necessary as the laser beams passed from air into a curved acrylic tube and finally into the water flow medium. A small degree of optical malalignment was present even after index matching and the two control volumes were slightly displaced with respect to each other, the amount of received reflected light was also diminished.

LDA measurements through different windows (incidence points on the tube walls) also changed the intersection angle (two half angles) between the beams. however, the change of this angle did not change the fringe spacing (d_f) as the wavelength also changed according to the refractive index of the test medium (TSI incorporated 1994) as follows:

The path of alight beam crossing from one medium to another one is described Snell's law:

$$N_1 \sin \alpha_1 = N_2 \sin \alpha_2$$

where N is the refractive index of the medium

 α is the angle between beam and the surface normal.

Fringe spacing, if measured in air without any window, is:

$$d_f = \frac{\lambda_A}{2\sin\alpha_A}$$

(Equation 3-3)

(Equation 3-2)

where λ_A is the wavelength of laser light in μm

 d_f is fringe spacing in μ m

 α is the half angle of the two intersection beams.





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The wavelength in the new medium is:

$$\lambda_f = \frac{\lambda_A}{N_f} \tag{Equation 3-4}$$

thus, fringe spacing for new medium is established from *Equations 3-2, 3-3* and *3-4* as follows:

$$d_{fA} = \frac{\lambda_f}{2\sin\alpha_f} = \frac{\frac{\lambda_f}{N_f}}{\frac{2\sin\alpha_A}{N_f}} = \frac{\lambda_A}{2\sin\alpha_A}$$
(Equation 3-5)

This value remains unchanged and means that the magnitude of velocity measured through different windows (ie. for a change in optical medium) does not change.

This does not mean that the change in optical medium is entirely aproblematic: (a) the location of measurement volume is not correct leading to measuring in wrong place and (b) measurement volumes of horizontal and vertical beams are located in

different places due to laser beams passing through different geometries within the test section and leading to erroneous results for shear stresses. Except Chew *et al.*'s study (1993), all the heart valve studies using LDA in literature up to date, did not mention how to solve and compensate for these problems. In order to solve these problems, the geometry of the test sections was analysed as follows:



Figure 3-9 Horizontal beams through index matching windows

The horizontal beams were used for measuring axial velocities. These beams were not affected by the curved window, however they passed through the index matching box so that the location of measurement volume changed due to the variation of refractive indexes. The actual focal distance F_a was calculated using Equation 3-6 (TSI incorporated 1994).

$$F_a = F \times \frac{\tan \alpha_A}{\tan \alpha_f} + t(1 - \frac{\tan \alpha_w}{\tan \alpha_f}) + d(1 - \frac{\tan \alpha_A}{\tan \alpha_f})$$
 (Equation 3-6)

where F_a is the actual focal distance in mm

F is the given focal distance of lens in mm

t is the thickness of window in mm

d is the distance from lens to window in mm.

As can be seen from *Equation 3-6* and the maximum tolerance on the location of the horizontal beams measurement volume occurred at the far side tube wall.

The vertical beams were used for measuring tangential velocities, these beams were affected not only by the index matching windows, but also by the curved window (see *Figure 3-10*). As a result, the location of this measurement volume changed differently from the location of measurement volume of the horizontal beams. This phenomenon impacted on shear stress measurements as shear stress calculations were based on coincident velocities.

In order to reduce these problems, such as the movement of the correct measurement volume and the difference of the location of the two measurement volumes, medical grade paraffin was filled in the index matching box and the actual movement of probe was calculated using Equation 3-6. The actual movement of the probe of 0.8 mm was decided for measuring axial velocities exactly at every 1 mm in test sections as axial velocity profile is dominant over tangential velocity in investigating heart valve flow. Measurement volume of the horizontal beams was exactly adjusted for measuring axial velocities in the correct positions. However, the location of vertical beam measurement volume was still different from the location of the horizontal measurement volume. The difference between the two locations was calculated using equations found in previous study (Chew et al. 1993). Maximum alteration of 2.5 mm was calculated in the centre of tube, this causes affects on the result of shear stresses. However, shear stress does not change very much because (a) maximum alteration of 2.5 mm is of the same order of magnitude as the measurement volume (1.5 mm), (b) tangential velocities and their fluctuations do not change significantly along radial position, (c) axial velocities plays a dominant role over tangential velocities (see Equation 5-20) in calculating shear stresses, and (d) axial velocities were measured in correct positions.



Figure 3-10. Vertical beams through curved window

Two velocity components (U and V, axial and tangential, respectively) and stress measurements were recorded at five planes in the upstream and downstream region of the valves and orifices eg. at 1 diameter (19 mm) upstream of the valve seating ring or orifice plate location, and at four positions downstream: 1, 2, 3 and 6 diameters. At each measuring plane, 18 data points from 1 mm to 18 mm radially (within the 19 mm internal diameter tube) were recorded, in. 1 mm radial steps. This provided a good picture of the structure and subsequent development of the flow (see *Figure 3-11*). This constituted one velocity data set.

LDA velocities were measured under both steady and pulsatile flow conditions then analysed for mean and fluctuating velocity components. The mean velocity components were plotted to determine flow properties such as velocity profile, vorticity, stagnation and recirculation regions which are known to promote thrombus formation and tissue overgrowth. The fluctuating components were used for calculating Reynolds shear stresses which cause lysis effects on blood cells. In this study, steady flow shear stresses were calculated from maximum of 6000 coincident data points collected in each of the two orthogonal directions and then plotted versus radial position to compare shear stress fields of different orifices. Pulsatile velocities in the Jellyfish valve were measured over 8 cycles then analysed for shear stresses (see *sub-section 3.2.3*)



Figure 3-11. Velocity measuring planes

3.2.4 Pressure drop and volumetric measurements

Pressure drops across orifices were measured only under steady flow conditions at flowrates of 100 to 417×10^{-6} m³/s (25 l/min). Whereas pressure drop measurements across the Jellyfish valve were made under the steady and pulsatile flow conditions described in *sub-sections 3.2.1* and *3.2.2*.

All pressure measurements were made using wall pressure taps located ± 6 diameters downstream and upstream of the location of valve or orifices. According to ASME (1959) these pressure drops are actually pressure losses caused by the obstruction of orifices. Pressure taps consisted of four holes around the tube wall (see *Appendix 1*) so that average static pressures were measured representing upstream or downstream

static pressures. Pressure drops were the difference between upstream static pressures and downstream static pressures.

$$\Delta P = P_{Upstream} - P_{Downstream}$$
(Equation 3-7)

where ΔP is the Pressure drop (kPa)

 $P_{Upstream}$ is the static pressure in the upstream region

 $P_{Downstream}$ is the static pressure in the downstream region.

In this case, the error of pressure drop measurements caused by instruments is calculated as follows:

$$\delta P = P_{Maximum} \times \delta\% \tag{Equation 3-8}$$

where δP is the absolute error (kPa)

 $P_{Maximum}$ is the upper measuring limit of the of pressure the transducers (kPa) $\delta\%$ is the accuracy of pressure transducers.

As indicated by *Equation 3-8*, in order to reduce the error of pressure drop measurements, the measuring range of pressure transducers was reduced. This was possible only when the measured static pressures were kept as low as possible, hence two small pumps were installed in parallel (see *sub-section 3.2.1*).

In steady flows, pressure drop measurements across orifices were analysed for empirical equations to calculate pressure coefficient (Cp) and effective area of orifices. In pulsatile flows, pressures and flowrates were measured over eight cycles in the Jellyfish valve then analysed using 5° binning analysis (see *section 4.2*) for mean values. Pressure drops, regurgitant flow and energy losses of the valve were calculated using *Equations 4-11, 4-12* and *4-16*, respectively. All pressure transducers used in this study were disposable, physiological blood pressure transducers². The strain gauge conditioners fabricated at The University of Adelaide.

² PVB 2-PDPT-3003S

Steady pressure drops and flowrates across different orifices were presented in *section 5.1*. Pulsatile pressure drops and flowrates were measured only across the Jellyfish valve and their analysis and discussions were shown in *section 5.5*.

This study was carried out using experimental techniques which usually deal with complicated flow problems. In experiments, data analysis plays a very important role in making experimental data become useful and meaningful. The role of different data analysis techniques is to package and transmit experimental information efficiently from an experimenter to other researchers. As an example, LDA measures instantaneous velocities over a period of time. These velocity data themselves do not say any thing about heart valve flow characteristics: instead, data needs to be analysed to yield mean velocities, turbulence intensities and shear stresses to enable flow comparisons between heart valves. This illustrates the importance of the data analysis role. Chapter Four presents some techniques for analysing LDA velocity and pressure drop data.

4.1 LDA velocity data analysis

In this study, LDA was used for measuring axial and tangential velocities, which are instantaneous and can be divided into two components as follows:

$$u = U + u'$$

(Equation 4-1)

where *u* is the instantaneous velocity component

U is the time averaged mean velocity component

u' is the fluctuating velocity component.

The instantaneous velocity component (u) itself does not say anything about the flow characteristics of heart valve flows; whereas the axial, time averaged mean velocity component (U) is important as it provides information about stagnation and recirculation regions which promote thrombus formation and tissue overgrowth, and on velocity profiles which indicate jetting. High turbulence intensity and Reynolds shear stresses in blood flow indicate haemolysis; these are derived from the fluctuating velocity components following analysis by Reynolds algebra. Methods for extracting mean velocities, turbulence intensities and Reynolds shear stresses are developed here for use as predictors of haemodynamic parameters.

Time averaged mean velocities are calculated from n instantaneous data points gathered in a fixed time period:

$$U = \frac{\sum_{i=1}^{n} u}{n}$$
 (Equation 4-2)

Turbulence intensity is calculated as follows:

$$TI = \frac{\sigma_u}{U} \times 100 \qquad (Equation \ 4-3)$$

where $\sigma_u = \frac{\sum_{i=1}^{n} (u^2 - U^2)^{0.5}}{n}$ is the velocity standard deviation.

Haemolysis is red blood cell damage due to mechanical forces acting within the blood, especially in a region where high Reynolds shear stresses are acting. The mechanisms of haemolysis are stretching of the blood cell membrane and irrevocable changes harmful to the cell's essential function. Reynolds shear stresses can be calculated from any orthogonal fluctuating components (Stevensohn *et al.* 1985). For example:

$$\tau_{x\theta} = \rho \ \overline{u'v'} \qquad (Equation 4-4)$$

where u' and v' are axial and tangential fluctuating components, respectively.

 ρ is the density of fluid.

In this study, Reynolds shear stresses in steady flow are calculated from n coincident data points collected in each of the two orthogonal directions, axial and tangential, (yielding the u and v velocity components) by the following equations:

$$\tau = \frac{1}{n}\rho \sum_{1}^{n} (u - U)(v - V) \qquad (Equation 4-5)$$

where n data points were measured over a period of time
u and v are the instantaneous velocity components U and V are time averaged mean values calculated from n data using Equation 4-2.

Analysed data, such as mean velocities, turbulence intensity and shear stresses are plotted versus radial positions to provide graphical flow field data for the various orifices, so that these parameters might be easily compared between orifices.

Analysing LDA velocity, pressure drop and flowrate measurements in pulsatile flow is more difficult because measured data are dependent on the time of cyclic flow. Consequently, time averaged mean, fluctuating values, turbulence intensity and shear stresses are not able to be produced directly from *Equations 4-2, 4-3, 4-4* and *4-5*. In order to gain these parameters in cyclic flows, 5° binning analysis is introduced in the next section.

4.2 The 5° binning analysis

Experimental data viz: velocities, flowrates, and pressure drops were measured under both steady and pulsatile flow conditions. Data in steady flow at each point was taken over a period of time, from this instantaneous data, time averaged mean and fluctuating components were calculated as simple arithmetic averages. From these averages, turbulence intensity and shear stresses can be calculated (see *section 4.1*). On the other hand, pulsatile flow parameters are dependent on low frequency cycles, thus time averaged mean and fluctuating values are not easily gained. In order to ascertain these values, data from pulsatile flow, such as velocities, pressure drops and flowrate, was measured over several cycles and then analysed for time varying mean and fluctuating components imposed on a low (carrier) frequency using a 5° binning analysis.

In the 5° binning analysis, data from each cycle is divided into 5° segments which were compiled into bins with corresponding data from subsequent (360°) cycles and averaged to yield fluctuating and mean components (see *Figure 4-1*).



Figure 4-1. 5° binning analysis

Mean components over several cycles can be manipulated into one representative cycle as follows:

$$C_s = \frac{\sum_{i=1}^n \sum_{j=1}^m C_{ij}}{nm}$$

(Equation 4-6)

where C_s is the mean component of segment s

 C_i are the instantaneous components contained within a segment of the cycle n is the number of data points in a segment

m is the number of cycles measured.

As can be seen from *Equations 4-1* and 4-2, time averaged mean and fluctuating values in steady flow become more accurate if the amount of measured data or

measuring time is increased. However, in pulsatile flow, time increases lead to a spread of values and a smoothing of essential data; the quality of the averaged mean and fluctuating values depend on the size of the bins, the number of cycles measured and Reynolds number or turbulent intensity (Jin and Clark 1994). The number of cycles required for calculating the average value should be large and the size of the bins should be small enough so that the average value converges to a single value with a minimal standard deviation. Furthermore, the convergence of the mean value in pulsatile flows is quicker when the Reynolds number in the flow is smaller (Jin and Clark 1994). The bin size of around 15 ms and the number of data points of 100 to 300 was chosen in the previous study (Schoephoerster and Chandran 1991). In the more recent study Jin and Clark (1994) suggested to calculate the number of cycles measured with a fixed correlation factor so that a minimal standard deviation of the mean value in cyclic flows could be obtained.

In this study, pulsatile data such as pressure drops, flowrates and velocities were measured at maximum Reynolds number of 27,000. Data was taken over 8 cycles with a bin size of 11.57 ms corresponding to 5° in a 1.2 Hz (72 beats/min) cycle; this yielded average values with a correlation factor of 98%.

4.3 Dimensional analysis

Dimensional analysis is a packaging or compacting technique used to reduce the complexity of experimental programmes and at the same time increase the generality of experimental information. Data from steady flow tests eg. pressure drops are analysed using dimensional analysis techniques to give the most essential formulae to describe pressure losses through prosthetic heart valves. According to Buckingham's Π (Pi) theory (Gerhart and Gross 1985, Barenblatt 1987), any physical system can be expressed by a dimensionally homogeneous equation of the following form:

$$\pi_d = k \times f(\pi_1) \times f(\pi_2) \times \dots \times f(\pi_n)$$
 (Equation 4-7)

where $f(\pi_i)$		are transformation functions			
	$\pi_d, \pi_1, \pi_2,, \pi_n$	are terms of a complete set of dimensionless products			
	π_d	dependent dimensionless product			
	$\pi_{I}, \pi_{2},, \pi_{n}$	independent dimensionless products			
	k	exponential constant dependent on the values			
		of the respective dimensionless products.			

The concept of the component equations can be applied to obtain the prediction equation in the form of the *Equation 4-7*. Data obtained from a set of experiments in which only one π -term was varied while keeping all the other π -terms constant can be used to find a component equation in the following form:

$$\pi_d = a_i \pi_i^{k_i} \tag{Equation 4-8}$$

where a_i and k_i are constants dependent on the experimental results and the other π -terms were held constant. *Equation 4-8* can be rewritten in the following form:

$$\pi_d = k_i \times f(\pi_i) \tag{Equation 4-9}$$

It can be seen from Equation 4-9 that the transformation function $f(\pi_i)$ can be obtained by plotting the experimental data of π_d versus π_i in each set of experiments designed by the concept of component equations as mentioned above and the standard curve fitting procedures are applied here to find out component equations.

In this study, pressure drops across orifices and occluders were collapsed for pressure coefficient using dimensional analysis. Firstly, all the variables such as flowrate, orifice area, orifice and occluder position and orifice shape were taken into dimensionless terms (independent dimensionless products) such as Reynolds number (Re), ratio of orifice area to tube area (r_A), eccentricity percentages (E) and shape factors (Φ_{Shape}). Secondly, pressure coefficient (the dependent dimensionless product) was plotted versus each of the independent variables which were gained experimentally. Thirdly, standard curve fitting procedures were applied to these

plots to establish five component equations. Finally, the five component equations were combined in the form of Equation 4-9 to establish pressure coefficients across any orifices. The k_i constants were determined from each set of experiments in which only one π -term was varied while keeping all the other π -terms constant. The mean value of different constants k_i was the constant of the complete equation determined from experiments (for more detail, see section 5.1).

4.4 Pressure drops - effective orifice area

Pressure drops across prosthetic heart valves do not say very much about valve performance or lend much to comparisons between various valves. The introduction of effective orifice area and performance index of heart valves has made the valve comparison more complete. The effective orifice area of a heart valve can be calculated using Gorlin and Gorlin's (1951) formula:

$$A_{effective} = \frac{Q}{C \times 44.5 \times \sqrt{\Delta P}}$$
 (Equation 4-10)

where C is the discharge coefficient

 ΔP is the pressure drop across the valve in cm of H₂0

Q is the flowrate in cm³/s.

and
$$\Delta P = P_{Upstream} - P_{Downstream}$$
 (Equation 4-11)

where $P_{Upstream}$ and $P_{Downstream}$ are static pressure in the upstream and downstream region, respectively.

The valve performance index is defined as the ratio of effective orifice area to the valve ring area (Woo et al. 1983 and Heiliger 1987).

$$PI \equiv \frac{A_{Effective}}{A}$$

where $A_{Effective}$ is the effective orifice area of the valve

A is the valve ring area.

Generally, prosthetic heart valves are compared for effective orifice area and efficiency index. In this study, pressure drops were measured across different orifices and effective orifice areas were calculated using *Equation 4-10* to establish the effects of the orifice shape and position on effective orifice area of valves.

4.5 Energy losses and regurgitant flow

Regurgitant flow and energy losses indicate a valve's proper functioning. Large energy loss may lead to dysfunction of the heart; high regurgitant flow implies the valve's incompetence (failure to close properly), and large leakage produces very high retrograde velocities and a high shear stress region which may damage red blood cells. Regurgitant flow and energy losses are investigated carefully in recent studies eg. Teijeira and Mikhail (1992).

Regurgitant flow includes both backflow (during the closing phase) and leakageflow (in the closed phase) over a cycle and can be calculated as follows:

$$Q_{Regurgitant} = \frac{1}{n} \int_{0}^{T_2 + T_3} q \, dt \qquad (Equation 4-12)$$

where q is the flowrate through the value

n is number of cycles measured

T is the time of a cycle and the cycle is divided into three distinct phases:

 T_1 is the time period of forward flow (systole)

 T_2 is the time period of closing phase; and

 T_3 is the time period of closed phase, then:

$$T = T_1 + T_2 + T_3$$
. (Equation 4-13)

Total flow for one cycle is:

$$Q_{Total} = \frac{1}{n} \int_{0}^{T} q \, dt \qquad (Equation \, 4-14)$$

Relative regurgitant flow is defined as follows:

$$Q\% = \frac{Q_{Regurgitant}}{Q_{Total}} \times 100\%$$
 (Equation 4-15)

Energy loss is the product of flowrate and pressure drops, and this occurs in three distinct stages. For example, in the aortic position, these three energy loss stages are: (a) resistance of forward flow during systole; (b) reverse flow during closing and (c) leakage flow during the closed phase. Energy losses are calculated using the following equation:

$$\Delta E = \frac{1}{n} \int_{0}^{T} q \Delta P \quad dt \qquad (Equation \ 4-16)$$

where ΔP is pressure drop across the valve

 ΔE is average energy loss over a cycle.

Relative energy loss is defined as the ratio of energy loss ΔE to total energy:

 $E\% = \frac{\Delta E}{E_{Total}} \times 100\%$ (Equation 4-17)

where $E_{Total} = \frac{1}{n} \int_{1}^{T} q \times P_{Upstream} dt$ is total energy.

In this study, a prosthetic heart valve prototype called the Jellyfish valve was investigated. Relative regurgitant flow and energy losses across this valve were calculated using *Equations 4-15* and *4-17* to indicate the valve functioning and then were compared with those of other prosthetic heart valves. Generally, regurgitant flows and energy losses are from 6-12 % for mechanical valves (Teijra and Mikhail 1992) and 1-4% for bioprostheses (Woo *et al.* 1983). Maximum regurgitant flow of 4% and energy loss of 3.5% was observed in the Jellyfish valve.

The use of prosthetic heart valves, to replace defective aortic or mitral natural ones, is a common practice in surgery. However, implantation of these valves may causes problems for some patients. Some of these problems are directly related to the nature of the blood flow through the valves. Haemolysis, red blood cell damage, arterial wall damage, thrombus formation and high pressure drop are the most frequently observed problems. This chapter presents and discusses pressure drops, velocity profiles and shear stress fields in light of experimentation conducted as part of this study.

5.1 Steady flow pressure drops

Pressure drop measurement is one the most important factors in comparing and evaluating the insufficiency of heart valve prostheses; it can be used to compare relative performances of different valves or as an aid to future valve design (Gentle 1977 and 1984). Furthermore, from pressure drop measurements, effective orifice area and performance index can be calculated using the Gorlin and Gorlin formula (Gorlin - Gorlin 1951). Heiliger in 1987 investigated five different heart valves in a mock circulation during pulsatile flow conditions and found that the mean orifice area determined by him and the effective orifice area calculated using the Gorlin formula was in disagreement; he does not postulate reasons for this. Steady state pressure drop versus flow rate measurements were shown by Yoganathan *et al* 1979a to correlate well with mean cyclic pressure drops versus r.m.s. flowrate during systolic ejection from pulsatile flow data. In 1984, Swanson compared pressure drops were significantly different, which he attributed to:

- different geometries in the test regions into which the valves were inserted,
- different approach flow conditions,

- different placement of pressure measurement taps and
- different methods of pressure measurement.

This section simply focuses on pressure losses caused by the presence of valves in a smooth tube by modeling different orifices. This procedure may simplify or even replace the need to measure pressure drops through prosthetic heart valves and compare different heart valve types without any differences just by measuring geometries of the valves.

Four pressure drop measurement tests were carried out through different orifices to establish the effects of orifice area, position and shape and the occluder position on pressure drops. Pressure drops are a function of orifice areas, flowrate, orifice shapes and orifice or occluder positions. Dimensional analysis was used to aid analysis of collected data. All variables were changed to dimensionless products eg. pressure drop becomes pressure coefficient and so on.

For pressure drops:

$$C_{p} = \frac{\Delta P}{\rho \frac{U^{2}}{2}}$$

For flowrates:

$$R e = \frac{UD}{v}$$

For orifice areas:

$$r_A \equiv \frac{A_1}{A_0}$$

where A_1 is orifice area and A_0 is the tube area.

And finally for eccentricities:

$$E = \frac{\text{Eccentricity (mm)}}{D (mm)} \times 100\%$$

where *E* is the percentage eccentricity

D is the internal diameter of the tube; or the diameter of the ball occluder.

So pressure coefficient can be written in the following form:

$$C_{\rm P} = f(r_{\rm A}, {\rm Re}, E) \tag{Equation 5-1}$$

where C_p is the dependent dimensionless product and r_A , Re and E are independent dimensionless variables. Using equations 4-4 and 4-5, C_p can be rewritten as follows:

$$C_{\rm P} = k \times f(r_{\rm A}) \times f({\rm Re}) \times f(E) \qquad (Equation 5-2)$$

where f are empirical equations. These equations are obtained by plotting the experimental data for C_p versus each independent dimensionless variable in each set of experiments, called component equations, these are shown in *Figures 5-2, 5-4, 5-6* and 5-8. Standard curve fitting procedures are applied to these figures to establish their component equations.

5.1.1 The effects of the orifice area on pressure drops

Firstly, steady flow pressure drops measurements were conducted for flow through different circular orifices with flowrate range of 100 to 417×10^{-6} m³/s (6 - 25 l/min) corresponding to the peak systolic flowrate of cardiac output of 33.3 to 91.7 ×10⁻⁶ m³/s (2 - 5.5 l/min). These circular orifices had the same geometric characteristics but different areas. The ratio of orifice area to tube area (r_A) was chosen to be in the range 0.4 to 0.75 corresponding to the ratio of orifice area to sewing ring area of the most commonly used heart valve prostheses (the ball valve is the most obstructive and has a ratio of orifice area to sewing area of 0.4, and the bileaflet valve is the least obstructive and its ratio is about 0.75).



Figure 5-1. Pressure drop versus flowrate squared for flow through circular, concentric orifices of diameters 16.5, 15, 13.5 and 12 mm

Pressure drops in kPa are plotted versus the square of flowrates. Data points from each orifice are on a straight line, this agrees with other investigators' work eg. Gentle (1977). As can be seen, *Figures 5-1, 5-3, 5-6* and *5-4* show that pressure drop decreases when orifice area or r_A increases. Pressure drops change dramatically when r_A changes from 0.4 to 0.75. At a flowrate of 417×10^{-6} m³/s (25 l/min) this change is 1000% (from 5.4 to 0.56 kPa). This means that the flow area of prosthetic heart valves is a very important factor in reducing or increasing pressure losses through orifices, and hence prostheses.

Furthermore, data points were condensed (collapsed) against Q^2/d^4 , where Q is flowrate and d is the orifice diameter. As can be seen from *figure 5-2*, data points of this study were not on a straight line and gave a disagreement with Gentle's 1977 and 1984 studies; in which pressure drops were measured across a type of valve with different sizes, and data points were collapsed against Q^2/d^4 giving a straight line. This lead to an expectation that in this study, pressure drops versus Q^2/d^4 of a circular orifice with different sizes should lie on a straight line; this was not the case. The main reason which caused the difference between two studies, is the fact that the pressure drop across orifices in this study was measured in tube, whereas Gentle was mounting the valve between two relatively large chambers. So that most of the pressure drop was caused by dissipation of the velocity head of the jet issuing from the valve and then slowing down in the downstream chamber. (Gentle, 1995). This shows the gross differences between viscous, boundary layer flow (in the tube) and relatively inviscid, potential flow (between large vessels).



Figure 5-2. Condensed pressure drops across circular orifices for flow through circular, concentric orifices of diameters 16.5, 15, 13.5 and 12 mm

As can be seen from *Figure 5-1*, pressure drops depend greatly on the orifice area and flowrate or, in other words, on the r_A and Reynolds number. *Figures 5-3* and 5-4 show pressure coefficient C_p versus r_A and Reynolds number, respectively. Pressure drop increases, whereas pressure coefficient reduces with increasing Reynolds number. Pressure coefficient at low Reynolds numbers reduces quickly then slow down; at high Reynolds numbers it seems to be steady (see *Figure 5-4*). Pressure coefficient reduces dramatically from 5.9 to 0.6 when r_A changes from 0.4 to 0.75 (see *Figure 5-3*).



Figure 5-3. Pressure coefficient versus r_A for various Reynolds numbers of flow through circular, concentric orifices

The first component equation is the function of r_A which can be obtained from *Figure 5-3*. As can be seen from *Figure 5-3*, the pressure coefficient increases exponentially when r_A reduces from 0.75 to 0.4. In order to get a better curve, a boundary condition should be inserted here: when $r_A = 1$; this corresponds to pressure loss in flow through a 19 mm internal diameter tube. This value was calculated from Darcy-Weisbach equation, pressure loss and pressure coefficient are as follows:

pressure loss:

ł

$$\Delta P_L = f \times (\frac{L}{D}) \times (\frac{\rho U^2}{2})$$
 (Equation 5-3)

and pressure coefficient:

$$C_{\rm p} = \frac{\Delta P_L}{\frac{1}{2}\rho U^2} = f \times (\frac{L}{D})$$
 (Equation 5-4)

where L: is tube length

D: is tube internal diameter

f: is the Darcy friction factor for smooth and fully developed turbulent flow.



Figure 5-4. Pressure coefficient versus Reynolds number for varying area ratios of circular, concentric orifices in tube flow

The friction factor (f) can be expressed as a function of Reynolds number in a smooth tube as follows:

$$f_{Smooth} = 0.3164 \text{ Re}^{-1/4}$$
 (Equation 5-5)

Using equations 5-3, 5-4 and 5-5, $C_p = 0.3126$ can be calculated as $r_A = 1$ and then using curve fitting procedure on *Figure 5-3*, the first component equation can be determined as:

$$C_{\rm Pr} = 0.473249 + 270.05902 \times e^{\left(\frac{-7.7}{0.1002386}\right)}$$

(Equation 5-6)

the correlation factor r of this equation is:

$$r_1^2 = 0.999068$$

The second component equation is of the function of Reynolds number, the pressure coefficient seems to have an exponential relationship with Reynolds number. This equation can be obtained from *Figure 5-4* using the curve fitting procedure:

$$C_{pR} = 5.294376 + 10.382888 \times e^{\frac{-Re}{3302.9157}}$$
 (Equation 5-7)

and the correlation factor *r* is:

 $r_2^2 = 0.972834$

5.1.2 The effects of the orifice position on pressure drops and effective orifice area

Secondly, pressure drop measurements were conducted through a circular orifice mounted within the tube with differing degrees of eccentricity. The circular orifice was positioned by a screw within the orifice housing to introduce the eccentricities (see *Appendix 1*). These eccentricity was adjusted in 0.5 mm steps from 0 (centre line of the tube) to 3.5 mm off the centre line providing a very good picture of pressure drops caused by eccentricity

$$E = \frac{\text{Eccentricity (mm)}}{\text{Tube diameter}} \times 100\%$$
 (Equation 5-8)

Pressure drops were plotted versus the square of flowrate dependent on eccentricities. Larger eccentricities caused larger pressure drops, and pressure drops increased by 23% (from 5.4 to 6.6 kPa) at a flowrate of 417×10^{-6} m³/s (25 l/min) when *E* increased from 0% to 30% (see *Figure 5-5*). As can be seen from these measurements, eccentricity does not affect pressure drops as much as the orifice area and orifice shape do. *Figure 5-6* shows pressure coefficient C_p versus eccentricity percentage *E*. The coefficient of pressure, C_p, increased with increasing eccentricity: at the first stage, when the eccentricity is small, the pressure coefficient increases

slowly; later this increases more rapidly and it seems to have a second-order relationship with E. Here again, pressure coefficient reduces with the increasing of Reynolds number.



Figure 5-5. Pressure drop versus flowrate squared for various eccentricities of an orifice of 12 mm diameter ($r_A = 0.4$)



Figure 5-6. Pressure coefficient versus eccentricity percentage for various eccentricities of an orifice of 12 mm diameter ($r_A = 0.4$)

The third component equation is the function of the eccentricity percentage E, this equation can be obtained from *Figure 5-6* using the curve fitting procedure:

$$C_{PE} = 5.371233 + 0.004281 \times E^2 \qquad (Equation 5-9)$$

The correlation factor *r* is:

$$r_3^2 = 0.993978$$

Effective orifice area of a circular orifice located with different eccentricities (different positions) was calculated after Gorlin and Gorlin (1951) (*Equation 4-6*). For comparison, C, the discharge coefficient was considered to be 1. The results were calculated and are shown in *Table 5-1*.

Table 5-1. Effective orifice area of an eccentric orifice of constant diameter (12 mm)

E	0	2.63	5.26	7.89	10.53	13.16	15.79	18.42
$A_{Effective} (\mathrm{cm}^2)$	1.19	1.18	1.17	1.15	1.14	1.12	1.10	1.06
CPosition	1.00	0.989	0.979	0.966	0.954	0.939	0.917	0.888
measured								

As can be seen from this table the real orifice was unchanged, because measurements were carried out across only one orifice, but the orifice position was changed with eccentricities of 0 to 3.5 mm, consequently, pressure drop changed. Due to changing of pressure drops across the orifice, effective orifice area changed as well. The position coefficient is defined as a ratio of effective orifice area at any position of the orifice to effective orifice area of central flow orifice as:

$$C_{Position} = \frac{A_{Effective \ eccentric}}{A_{Effective \ concentric}}$$
(Equation 5-10)

The position coefficient seems to be a function of the eccentricity percentage E of the orifice and can be established from *Table 5-1* using the curve fitting procedure:

$$C_{Position} = 0.987672 - 0.000290 \times E^2$$
 (Equation 5-11)

with correlation factor

5.1.3 The effects of the occluder position on pressure drops and effective orifice area

Thirdly, the effects of the occluder position on pressure drops when a 14.5 mm ball occluder was inserted into a 19 mm tube. The ball was moved within the tube to make different eccentricities (different occluder positions). Five positions of the ball were created in 0.5 mm steps from 0 (the centre line of the tube) to 2 mm off the centre line (for more detail see *Appendix 1*). Again here, pressure drops were measured in a flowrate range of 100 to 417×10^{-6} m³/s (6 - 25 l/min) then plotted versus the square of flowrate (*Figure 5-7*), the pressure coefficient was plotted versus eccentricity percentage *E* (*Figure 5-8*) where:

$$E = \frac{\text{Eccentricity (mm)}}{\text{Ball diameter (mm)}} \times 100\%$$
 (Equation 5-12)

The third component equation (Equation 5-9), the function of the eccentricity percentage E caused by the eccentricity of the orifice, can be applied to describe the relationship between coefficient of pressure and eccentricity of the occluder. This equation was obtained from Figure 5-6 and represents the data from Figure 5-8 within 5% error (see Appendix 3). Figure 5-8 shows the pressure coefficient measured through the ball of different eccentricities versus percentage eccentricity E.

The results show that the position of occluders and the position of orifices cause the same pressure drops and the third component equation can be used for all the orifice and occluder positions. From the last two measurement sets it can be seen that any eccentricity (of orifice or occluder) causes eccentric flow patterns downstream of the valve thus increasing pressure drops. This probably explains why pressure drops through the tilting valve is high in comparison with those of other valves with the same orifice diameter (Hanle *et al.* 1989). The tilting valve in an open position causes an eccentric flow downstream of the valve in the form of a major and a minor

orifice flows. This increases pressure drops through the valve even though the effective orifice area of this valve is relatively large.



Figure 5-7. Pressure drop of the occluder position versus flowrate squared for a ball occluder mounted with various eccentricities





Like the effects of the orifice position, the occluder position also affects the effective orifice area. In the same way, effective orifice area of a constant area orifice in different positions of the occluder can be calculated and a function of occluder position coefficient on eccentricities can be established.

E (%)	0	3.45	6.9	10.34	13.79
$A_{Effective} (cm^2)$	1.38	1.36	1.34	1.32	1.29
C _{Position} measured	1	0.985	0.972	0.961	0.935
C _{Position} calculated	0.988	0.984	0.974	0.957	0.933

Table 5-2. Effective orifice area and position coefficient of an eccentric occluder orifice

Equation 5-11 found in sub-section 5.1.2 was applied to calculating the position coefficient of the occluder position, and the results indicated a maximum error of 1.2% in the predictive quality of Equation 5-11. Furthermore, tables 5-1 and 5-2 show that effective orifice area not only depends on the orifice or occluder position, but also the orifice shape. Effective orifice area of an annular orifice is much larger than the real orifice area, thereby, it is worth investigating the orifice shape in the next section.

5.1.4 The effects of the orifice shape on pressure drops and effective orifice area

Finally, pressure drops were measured through constant area orifices with different shapes such as circular, triangular, square and annular. These shapes are similar to the shapes of the most commonly used heart valve prostheses when they are fully open. For example, the ball valve has an annular orifice shape, the bileaflet valve orifice is approximately circular and bioprosthetic and natural valves have orifices which may be approximated by triangular (trileaflet valves) or square (bileaflet) shapes.

Again, flowrates were varied from 100 to 417×10^{-6} m³/s (6 - 25 l/min) and orifices were inserted into a 19 mm tube. Results from this measurement set are shown in

Figures 5-9 and *5-10*. Pressure drops were not dependent on the hydraulic diameters of the differently shaped orifices as might be expected. According to Gerhart and Gross, hydraulic diameters of different duct shapes can be calculated by the following equation:

$$D_{h} = \frac{4A}{P} = \frac{4 \times (\text{Duct cross} - \text{sectional area})}{\text{Wetted perimeter}}$$
(Equation 5-13)

The annular orifice had the smallest hydraulic diameter of the four different shape orifices but pressure drops across the annular orifice were shown to be lowest. Whereas the triangular orifice had a smaller hydraulic diameter in comparison with the square and circular orifices, but the pressure drops were higher. This means that pressure drops do not depend on the hydraulic diameter, but on the orifice shape, or possibly, *Equation 5-13* cannot be applied for calculating hydraulic diameter of annular orifices.

Figure 5-9 shows pressure drops versus the square of flowrate, the data points of each measurement are on a straight line. Pressure drops depend on the orifice shape; except for the annular orifice, the pressure drop reduces with increasing hydraulic diameter of the different shaped orifices (with increasing hydraulic diameter orifice shape tends towards circular). As can be seen from Figure 5-9 the best shape is the annular shape, and pressure drop at a flowrate of 417×10^{-6} m³/s (25 l/min) changes 200% from the annular shape to the triangular shape (from 3.8 to 7.4 kPa, respectively). From these measurements it is shown that the shape of valves when they are fully open is the second most important factor after the orifice area and before the eccentricity. In fact, orifice area is a limiting condition: due to the valve size limitation, orifice area cannot increase easily and infinitely, but the shape of valves can be changed for better shapes more easily in order to reduce pressure drops. This could explain why pressure drops through the bioprosthetic valve are higher than those of the tilting and bileaflet valves (Hanle et al. 1989), because bioprosthetic valves, when open, create a triangular orifice and this shape induces higher pressure drops.



Figure 5-9. Pressure drop versus flowrate squared for orifices of equal area but different shape.

Figure 5-10 shows pressure coefficient versus Reynolds number for different orifice shapes. The pressure coefficient for the triangular orifice is the largest and that of the annular orifice is the smallest. Furthermore, the trend of the pressure coefficient versus Reynolds number of different shapes looks the same. At low Reynolds number, pressure coefficients reduce rapidly, then slow down. At high Reynolds number, they seem to remain steady (see *Figure 5-10*). As mentioned above, the pressure drop is not a function of the hydraulic diameter, but is dependent on the orifice shape. This study introduces a shape factor (Φ_{Shape}) which is used instead of the hydraulic diameter in the description of heart valve orifice configuration.

Pressure coefficient across any orifices are calculated based on a circular orifice with equivalent area then multiplied with shape factor as follows:

$$C_{P} = C_{P circular} \times \Phi_{Shape}$$
 (Equation 5-14)

where Φ_{Shape} is the shape factor and $C_{P circular}$ is the pressure coefficient of a circular orifice with equivalent area. The shape factor is defined as ratio of pressure coefficient measured from experiments of any shape orifice to circular orifice with equivalent area as:

$$\Phi_{shape} \equiv \frac{C_{P_{shape}}}{C_{P_{circular}}}$$





and the shape factor can be established from *Figure 5-10* by averaging from 7 data points. For annular orifices the shape factor is:

$$\Phi_{Annular} = 0.756$$

for square orifices the shape factor is:

$$\Phi_{Sauare} = 1.285$$

and finally, the shape factor of triangular orifices is:

$$\Phi_{Triangular} = 1.394$$

The actually measured orifice area of the four different shape orifices is the same and equal to 1.13 cm^2 . The effective orifice area of these orifices can be calculated using Gorlin and Gorlin formula (1951) (re: *Equation 4-10*).

For comparison, the discharge coefficient for each orifice was considered to be unity (C = 1), and the effective orifice area of the different shape orifices was calculated. The actual discharge coefficient C of these orifices is calculated from the ratio of the calculated to the measured area and now is defined as the shape coefficient C_{Shape}.

Table 5-3. Effective orifice area and shape coefficient of different shaped orifices

Shape	Triangular	Square	Annular	Circular
$A_{Effective} ({ m cm}^2)$	1.01	1.05	1.37	1.19
C _{Shape}	0.89	0.93	1.22	1.06

As can be seen from these results, due to the difference of pressure drops the calculated effective orifice area is significantly different from the theoretical orifice area ($A_{Actual} = 1.13 \text{ cm}^2$ for each shape). Discharge coefficients of the annular and circular orifice are larger than 1, here the discharge coefficient of the circular orifice is larger by 6% (see Table 5-3) probably due to the error in the instruments and the position of pressure taps along the tube (see Figure 2-2). The discharge coefficient of the annular orifice is equal to 1.22 which much larger than 1, this is due to its annular shape. This result is unexpected, because the discharge coefficient through any orifices were expected to be ≤ 1 (Gorlin and Gorlin 1951, ASME 1959). Discharge coefficients depend on the orifice shape as does the relationship between the effective orifice area and the actual orifice area. These results can imply that the comparison of calculated effective orifice area with the actually measured area obtained from an autopsy or during operation may lead to mis-evaluating discharge coefficient C. This is because the valve shape is different post-mortem or under open heart surgery compared with its shape under normal conditions. This is especially true for the patients with a prosthetic heart valve. For example, Horstkotte *et al.* (1983) calculated the mean value of effective orifice area of Björk-Shiley SD valves implanted in patients in the mitral position using the Gorlin and Gorlin formula and this value was 14% larger than the mean orifice area measured by Heiliger (1987) using a fibre-optic camera. This difference may be caused by the fact that the Gorlin and Gorlin formula did not take the orifice area of the Björk-Shiley valve as a annular orifice into account.

5.1.5 Summary of pressure-flow relationships

Finally, an equation of pressure coefficient through any primary orifices with flowrates of 100 to 417×10^{-6} m³/s (6 - 25 l/min) can be established from *Equations* 5-6, 5-7, 5-9 and 5-14 as follows:

$$C_{P} = \frac{C_{Pr} \times C_{PR} \times C_{PE}}{29.21423} \times \Phi_{Shape}$$
 (Equation 5-15)

with correlation factor *r* is:

$$r^2 = 0.98156$$

where C_{Pr} , C_{PR} and C_{PE} are from the component equations determined above Φ_{Shape} is the shape factor, in case of circular orifice $\Phi_{Shape} = 1$.

As can be seen from *Equation 5-15*, the effective orifice area of any orifice or heart valve calculated from the Gorlin and Gorlin formula is dependent on the orifice shape, orifice position, Reynolds number and the location of pressure taps, as pressure coefficient is a function of all of these variables. This study advises a method to calculate the real orifice area of valves based on the Gorlin and Gorlin formula (1951), this is developed in the following paragraphs.

Firstly, discharge coefficient is considered to be unity (C = 1), so that the formula becomes:

$$A_{Effective} = \frac{Q}{44.5 \times \sqrt{\Delta P}}$$
 (Equation 5-16)

Secondly, use *Equation 5-16* to calculate the mean effective orifice area, as the effective orifice area varies with the change of Reynolds number corresponding to flowrate of 100 to 417×10^{-6} m³/s (6 to 25 l/min).

Thirdly, the real orifice area is established considering the orifice shape and position coefficient determined in *sub-sections* 5.1.3 and 5.1.4 and the calculated real orifice area now can be written in the following form:

$$A_{real} = \frac{A_{Effective}}{C_{Position} \times C_{Shape}}$$
(Equation 5-17)

5.2 Velocity profiles

The blood flow through the natural valve is smooth and bathes the entire valve wall, reducing thrombus formation. The closing is perfect and the central opening does not alter the flow pattern, energy being a minimum. On the other hand, in the prosthetic valve, the occluder element and supplementary elements such as strut, hinge and cage produce a high disturbance in the blood flow, creating regions of accelerated flow, where separation and recirculation occur. The low velocity and recirculation regions increase the probability of thrombus formation (Figliola and Mueller, 1981). It is evident, therefore, that velocity profiles should be investigated carefully.

In previous studies, steady flow velocity measurements were generally conducted at flowrates of about 167 and 417×10^{-6} m³/s (10 - 25 l/min). These steady flowrates correspond to the peak systolic flowrate for cardiac outputs between about 33.3 and 91.7×10⁻⁶ m³/s (2 - 5.5 l/min) (Yoganathan *et al.* 1979a, b and c). In this study, velocity measurements through different orifices using LDA were conducted at a

flowrate of 417×10^{-6} m³/s (251/min) only, and then presented to investigate the effects of flow area, flow shape and occluder position on velocity profiles.

Orifices were inserted into a 19 mm internal diameter tube creating two distinct flow regions, upstream and downstream. In the upstream region, the flow pattern is a fully developed tube flow and in the downstream region, the orifice as stenosis in the entrance disturbs the fully developed flow, and causes jet-flow in the vicinity downstream of the orifice producing different turbulence phenomena.



Figure 5-11. Measuring planes across some orifice cross-sections.

Velocity measurements through each orifice called 1 measurement set were carried out at five positions such as 1D up-stream, 1D, 2D, 3D and 6D downstream in the horizontal plane through the centre line of the tube. At each measuring plane, velocities were measured every 1 mm increasingly along the radial position, providing a good picture of the velocity profiles of each orifice. Furthermore, measuring planes through each of the orifice types were chosen to coincide with the critical plane, where the most disturbed velocity profiles should be found, therefore the largest shear stresses can be observed (see *Figure 5-11*).

5.2.1 The effects of the orifice area on velocity profiles

The first measurement set was conducted through four circular orifices with different areas corresponding to $r_A = 0.4$ to 0.75. As can be seen from the results, upstream profiles are the same, symmetrical, fully developed and with low turbulence intensities, because entrance flow followed a flow straightener. The turbulence intensities here were always under 20% (for more detail see *Appendix 4.1*).

The flow structures downstream of different orifices appears to have been greatly affected by the orifice area. The four different area orifices can be compared with respect to velocity results obtained 19 mm downstream from the orifices during forward flow. The 12 mm diameter orifice (smallest area orifice) generated the highest mean velocity gradients (4.14m/s) in the centre line of the tube and was the only one to generate regions of separated and recirculated flow near to the tube wall, which could be seen in the plane data at 1D downstream (see *Figure 5-12*). Root mean square (r.m.s.) axial velocities were minimal on the centre line and got larger near to the tube wall. Tangential velocities got larger when the radial position moved further from the centre line. The 12 mm orifice generated the highest r.m.s. axial and tangential velocity through the 13.5, 15 and 16.5 mm diameter orifices were getting smaller and the turbulence intensities reduced in size when the orifice diameter was enlarging. Maximum axial velocity in the 16.5 mm diameter

orifice was only 1.86 m/s in comparison with the maximum velocity of 4.14 m/s in the 12 mm orifice.

Maximum velocity 2D downstream of the 12 mm diameter orifice was still very high (3.05 m/s) and the velocity profile at 6D downstream became flat, whereas the velocity profile at 6D downstream of the 15 mm diameter orifice was getting redeveloped and the 16.5 mm diameter orifice had already become fully developed. Consequently, pressure drops and shear stresses became very low with increasing orifice size, because lower disturbance produced lower pressure drops and shear stresses (Hanle *et al.* 1989).

As can be seen from *Figure 5-12*, in the first stage of the downstream region is plug flow, the length of this plug flow depends on the orifice diameter. The diameters of plug flows 1D downstream were 5, 6, 7 and 8 mm across for the 12, 13.5, 15 and 16.5 mm orifices, respectively. Plug flow length for the 12 and 13.5 mm orifices ended somewhere between the 1D and 2D positions, this length for the 15 mm orifice was about 2D, whereas the plug flow diameter for the 16.5 mm orifice was still about 3 mm at 2D downstream, this length ended somewhere between the 2D and 2.5D positions. These points indicate the end of the initial region of jet-flow. Beyond these points, the flow becomes fully developed jet-flow length depends inversely on the orifice diameter. For example, the fully developed jet-flow of the 12 and 13.5 mm orifices ended at 6D downstream, whereas for the 15 and 16.5 mm orifices it ended somewhere between 3D and 6D downstream (for more detail see *Appendix 4.2*).

As can be seen that large orifice flow area produces many advantageous haemodynamic characteristics, but the fact is that the flow area of prosthetic heart valves is not easy to increase due to the limitation of the valve size, and structure of the sewing ring. This gives an ideal to optimise the flow with different shapes of a given area in the next section.



Figure 5-12. Velocity profiles through four circular orifices.

Secondly, velocity measurements were conducted through four orifices with the same area but different shapes, such as circular, square, triangular and annular, again at a flowrate of 417×10^{-6} m³/s (251/min). As before, upstream flow was fully developed turbulent tube flow, turbulence intensities were under 20% and peaked near to the tube wall.

Like pressure drop, the maximum velocity change through the annular orifice was the lowest of all orifice configurations (with a value of 3.01 m/s, 1D down stream). For flow through the circular, square, and triangular orifices at 1D downstream, this value was 4.14, 4.44 and 4.02 m/s, respectively. The velocity gradient of the annular orifice was low, but velocity jetting was occurring very near to the tube wall. This may lead to very high wall shear stress which can damage the aorta wall.

The length of the recirculation region of the triangular orifice was the longest, as can be seen from velocity profiles at 1D downstream. Velocities of the triangular and circular orifice near to the tube wall were negative, whereas those of the other two orifices were zero or positive. Here the result was unexpected, when the velocity gradient through the annular orifice was the smallest and through the triangular was smaller than those through the square and circular orifice. This can be explained by firstly, the r.m.s. of axial velocity through the triangular orifice was very high (1.07 m/s in comparison with 0.27 m/s through circular orifice and 0.46 m/s through square orifice of maximum velocity point) and the results thereby were affected and led to an unexpected value. Secondly, as mentioned in *sub-section 5.2.1* the length of the initial flow region depends on the orifice diameter, specifically hydraulic diameter, so that the comparison of velocity profiles at fixed distance was not very practical.





Figure 5-13 shows the velocity profiles across four shape orifices, the first stage (plug flow) of the triangular and annular orifices was not observed as it ended at a position less than 1D downstream, and the nearest measuring plane to the orifice location was located at 1D downstream. The initial jet-flow of the square orifice just ended at 1D downstream and the circular orifice ended somewhere between 1D and 2D downstream.

In the second stage, the flow becomes fully developed jet-flow and the result here is unexpected like in the pressure drop measurements. The flow through the annular orifice became fully developed jet-flow somewhat quicker than those of the three other orifices, even though the annular orifice had the smallest hydraulic diameter. Velocity profile through the annular orifice became flat somewhere between 3D and 6D downstream, and at 6D downstream the flow has already become redeveloped turbulent tube flow, whereas the velocity profiles through the triangular, square and circular orifices became flat only at around 6D downstream. In fact, the velocity profile through the circular orifice became flat somewhat quicker than those of the square and then the triangular orifices and seems to depend inversely on the hydraulic diameter. These results can imply that the hydraulic diameter of annular orifices does not work for pressure drop measurements or velocity fields.

As can be seen from these results, the triangular orifice produced the highest r.m.s. axial and tangential velocity and then the annular orifice. The circular orifice generated the lowest r.m.s. axial and tangential velocity. A region of separation and circulation can be observed at 1D downstream of the circular orifice and triangular orifice, between the wedge of the triangle and the tube wall. Furthermore, mean tangential velocity through the annular orifice was the highest and at 1D downstream this maximum value was 0.45 m/s in comparison with 0.14 m/s of the triangular; 0.08 m/s of the square and 0.06 m/s of the circular (for more detail see *Appendix 4.3*). This means that the orifice shape as the shape of prosthetic heart valves when they are fully open is a very important factor in affecting and disturbing the flow downstream of valves, and creating the regions of stagnation and recirculating flow -

which promote thrombus formation and tissue overgrowth. Moreover, the shape dictates the magnitude of the r.m.s. velocities which also imply higher shear stresses.

5.2.3 The effects of the occluder position on velocity profiles

Velocity measurements were conducted for flow around a 14.5 mm ball inserted inside a 19 mm internal diameter tube to investigate the effects of the occluder position (eccentricity) on velocity profiles. The ball was located in three positions (see *Appendix 1*). Firstly, in the centre of the tube then it moved from the centre line to 1 and 2 mm off the centre line to make eccentricities. Like previous measurements, the velocities were recorded at a flowrate of 417×10^{-6} m³/s (25 l/min) and in 5 measuring planes - at 1D upstream, and at 1, 2, 3, and 6D downstream.

When the ball was located eccentrically, the orifice had two regions of unequal area available for forward flow, these are called the major and minor flow orifices. Due to the major and minor flow structure of these orifices, the flow fields, which are shown in *Figure 5-14* were very eccentric and dependent on the eccentricity of the ball.

When the ball was located at a maximum eccentricity of 2 mm, it caused the highest eccentric flow field in comparison with those of other measurement sets. A region of stagnation and recirculation was observed behind the ball which was approximately the same size as the 14.5 mm diameter ball. This region was still evident 1D downstream with a size of 3 mm on one side of the tube and in another side of the tube, a new stagnation and recirculation region was being created with a size of 5 mm because of the eccentric jet-flow downstream of the ball. This region reduced further from the orifice location and became zero at 2D downstream.

As eccentricity was reduced smaller stagnation and recirculation regions were generated. No further stagnation and recirculation regions were found at distances between 1 and 2D downstream of the 0 and 1 mm eccentrically positioned occluder.

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The recirculation region within 1D downstream of the concentric occluder was somewhat smaller than that of the 1 mm eccentric orifice (see 2D downstream velocity profiles of the 0 and 1 mm eccentric orifices). The velocity profile of the 0 eccentric orifice became flat somewhere between 3 and 6D downstream of the orifice and started becoming redeveloped at 6D downstream. Whereas, the velocity profiles of the 1 and 2 mm eccentric orifices at 6D downstream were still affected by the eccentric flow or in other words, affected by the major and minor flow orifices. The direction of the jet-flow changed from the near-side of the 1 and 2 mm eccentric orifice, velocity fields of the 1 and 2 mm eccentric orifices, velocity fields of the 1 and 2 mm eccentric orifices.

The velocity gradient and r.m.s. axial velocity of the 1 mm eccentric orifice at 1D downstream was somewhat higher than that of the 2 mm eccentric orifice, 1 and 0.9 m/s for mean axial velocity and 1.7 m/s and 1.67 m/s for r.m.s. axial velocity, respectively. According to Hanle et al. (1989), the high velocity gradients imply high shear stresses, so that shear stress here should be higher than those in the 0 and 2 mm eccentric orifices and results agreed with expectations (see *sub-section 5.3.3*). However, the results were unexpected, because the velocity gradient, r.m.s. axial velocities and shear stresses of the 1 mm eccentric orifice were larger than those of the 2 mm eccentric orifice. These results imply that the comparison of velocity profiles across heart valve prostheses at a fixed distance may lead to mis-evaluating turbulent phenomena of the valve, because different heart valves as well as different occluders produce different jet-flows downstream and their flow regions such as plug flow and fully developed jet-flow ends and starts at different positions. Thereby, velocity measurements at some planes cannot imply the whole turbulent phenomena of the valve, but it can show clearly the region of stagnation and recirculation flow, which promotes thrombus formation and tissue overgrowth. Furthermore, the magnitude of velocity gradient and its r.m.s value can also indicate the magnitude of shear stresses in that measuring plane only.

Though the velocity measurements were conducted for only three positions of the occluder, the tendency of the development of velocity fields is clear. Larger

eccentricity of the occluder induces larger stagnation and recirculation region and higher pressure drops which promote thrombus formation and tissue overgrowth, this agreed with Hanle *et al.'s* work (1989).



Figure 5-14. Velocity profiles through different occluder positions
5.2.4 Summary of velocity fields

The flow downstream of the orifices or valves is jet-flow, which consists of three stages; initial jet flow region, fully developed jet-flow and finally, redeveloped turbulent flow. At the first stage, plug flow can be observed, which separates at the edges of the orifice. Flow which is very close to the orifice (flow at the nozzle of the orifice) is simply a jet of uniform mean velocity separated from the surrounding fluid by a vortex sheet. With increasing distance from the orifice this vortex sheet is diffused by the action of molecular viscosity, and the region of plug velocities is tending to zero. Beyond this point, the rate of increase of thickness of the mixing length of the mixing layer is larger, and at several orifice diameter lengths the two mixing layers merge with each other and a fully developed jet-flow is established. At this point, plug flow disappears. This agrees with the theory of turbulent jets (Abramovich 1963).

According to Abramovich (1963) the maximum length of a jet in order to become a fully developed jet flow is :

$$L_{max} = 3d$$

where d is orifice diameter.

As can be seen from the results of this study, this length is about 2*d*, where *d* is the hydraulic diameter of orifices. Initial regions of the annular and triangular orifices cannot be observed in the results, because the closest velocity profile downstream of the orifice could not be located at the position less than 1D (19 mm), as the laser beams were obstructed by the orifice housing (see Appendix 1).

The second stage is the fully developed jet-flow, where no further plug flow can be found and mean velocity gradients became smaller further from the orifice location. The region between the end of the initial jet-flow and the beginning of the second stage is called a transition region. At the end of this stage the flow pattern again became plug flow and the velocity profiles became flat across the whole tube diameter; this occurred at about 3 to 7D downstream of the orifice, dependent on the hydraulic diameter, and the orifice and occluder position. Except in the concentric annular orifice, the length of the second stage flow depended inversely on the hydraulic diameter of orifices. Beyond this point, the flow pattern became redeveloped turbulent tube flow and this is the third stage.

As can be seen, three stage flows were observed downstream of orifices or heart valves and each stage occurred and ended at different positions downstream of their location. Comparison of velocity profiles of heart valves at the fixed positions such as 1 and 2D downstream can provide only the information of stagnation and recirculation region, otherwise it leads to incompatible practice, especially in the comparison of shear stresses.

5.3 Shear stress fields

For the determination of the effectiveness of artificial heart valves, not only pressure drops and velocity profiles, but also shear stress fields have to be taken into account. Reynolds shear stresses can be calculated from any orthogonal fluctuating components (Stevensohn *et al.* 1985):

$$\tau_{x\theta} = \rho \ \overline{u' v'} \tag{Equation 5-18}$$

where u' and v' are axial and tangential fluctuation components, respectively.

 ρ is the density of fluid.

$$u' \approx \pm \delta \ U \approx \pm \frac{\partial U}{\partial r} \times \delta \ r$$
 (Equation 5-19)

Furthermore, the mixing model assumes that the fluctuating velocities can be calculated (Gerhart and Gross, 1985) by:

and
$$u' \approx v' \approx -l \times (\frac{\partial U}{\partial r})$$
 (Equation 5-20)

where l is the mixing length and

U is the axial time average velocity of one point.

As can be seen from *Equation 5-18*, Reynolds shear stress is a function of r.m.s of axial and tangential velocities. Furthermore, *Equations 5-19* and *5-20* show that shear stress is dependent on the mixing length and mean axial velocity gradient. Larger r.m.s. velocities and larger velocity gradient imply larger shear stress. In this section, shear stresses were calculated from two measured velocity fluctuation components, axial and tangential, using LDA through different orifices to establish the effects of the orifice area, orifice shape and occluder position on shear stress fields. This procedure is necessary, because high shear stress induced by the disturbance of the presence of heat valves causes haemolysis and red blood cell damage.

5.3.1 The effects of the orifice area on shear stress fields

Velocities were measured using LDA through four circular orifices as mentioned in 5.2.1 sub-section and shear stresses were calculated using Equation 4-5, as measured data was instantaneous, with coincidence windows of 6 μ s and maximum data size of 6000 data points.

As mentioned above, the presence of the orifice as stenosis in the flow created two distinct flow regions, up- and downstream. In the upstream region, the flow was fully turbulent tube flow, and the results showed that fluctuating velocities and shear stresses were functions of radial position. These increased, with the radial position getting close to the tube wall, minimum values of fluctuations and shear stresses were evident at the centre line and maximum shear stresses of about 1 Pa in the regions near to the tube wall were observed. This result gave good agreement with Longwell's work (1966). Downstream, the flow was divided into three stages and the shear stress distribution of each measuring plane depended on its mean axial velocity profile, or the flow pattern of each flow stage. Velocity profiles of four circular orifices were clearly observed in the first two stages, the third stage was redeveloped turbulent flow and this was not very clear. The third stage could be

observed only at 6D downstream of 16.5 mm orifice, hence only the first two shear stress phases are discussed in the following sections.



Figure 5-15. The relationship between velocity and shear stress field in initial jet flow region

The first shear stress distribution belongs to the first stage, initial jet-flow. The shear stress distribution of this stage seems to have fourth order function relationship with radial positions. In the centre, where plug flow was observed, axial fluctuating velocities and velocity gradients were minimal and so shear stresses were down as well. Shear stresses had peak values at two points, where axial velocities were increasing to attain the plug flow velocity value (see *Figure 5-15*). This shear stress distribution can be observed at 1D downstream of the 12 and 13.5 mm orifices and at 1 and 2D downstream of the 15 and 16.5 mm orifices.

The second shear stress distribution seems to be second order function with radial positions and this belongs to the second stage flow, fully developed jet-flow. Shear stresses were minimal at the place near to the tube wall and were at peak value at the centre of the tube (see *Figure 5-16*). The second shear stress distribution can be

found at 2, 3 and 6D downstream of the 12 and 13.5 mm orifices and at 3 and 6D downstream of the 15 and 16.5 mm orifices.



Figure 5-16. The relationship between velocity and shear stress field in fully developed jetflow region

As can be seen from the shear stress results of four circular orifices, maximum shear stress value did not occur at 1D downstream of the orifice as expected, but did occur at different places from the orifice location dependent on the orifice area. This depended on the flow pattern downstream of orifices as well as prosthetic heart valves. Maximum shear stress of 83 and 45 Pa for the 12 and 13.5 mm orifices occurred at 2D downstream, respectively. Maximum shear stress of 8.6 Pa for the 15 mm orifice occurred at 2D and 3D downstream positions, however, mean absolute value (4.4 Pa) of 3D downstream measuring plane was larger than that (3.6 Pa) of 2D downstream measuring plane. This meant that velocity 2D downstream was still plug flow. Furthermore, maximum shear stresses of about 1 Pa for the 16.5 mm orifice were found at every measuring plane and these were very small in comparison with the error of the instrumentation (for more detail, see *Appendix 4.2*).

As can be seen from the results of shear stresses in the 15 and 16.5 mm orifices, maximum shear stress values were not distinct due to the error of measurements, however, mean absolute shear stress value was more suitable for the purpose of the comparison of shear stresses. It is evident, therefore, that shear stresses are better to be compared for mean absolute value of each measuring plane to avoid the error of experiments.

$$\tau_{mean} = \frac{\sum_{i=1}^{n} \left| \tau_{i} \right|}{n}$$

(Equation 5-21)

Maximum mean absolute value of each orifice occurred at the same measuring plane as the maximum value. The 12 mm orifice (the smallest area orifice) produced the highest shear stress of 83 Pa with an absolute mean value of 34.4 Pa at 1D downstream. Whereas the 13.5, 15 and 16.5 mm orifices had maximum mean absolute shear stresses of 19.9, 4.4 and 0.6 Pa, respectively.

It can be summarised, firstly, the magnitude of shear stresses depended on the ratio of orifice diameter to tube diameter (r_A). Maximum mean absolute shear stresses changed significantly from 34.4 to 0.6 Pa when r_A changed from 0.4 to 0.75.

Secondly, mean absolute shear stress at the beginning of the initial jet flow region was minimal, then it increased when the measuring plane moved further from the orifice location and was at a peak value at the transition region, where the initial jet-flow ended and fully developed jet-flow started. In this stage, the rate of the increase of thickness of the mixing length of the two mixing layers was larger with the increasing distance from the orifice, it led to larger shear stresses. In the fully developed jet-flow region, the mean absolute shear stress reduced when the measuring plane was moved further from the orifice location (see *Figure 5-17*). The mean axial velocity gradient and its r.m.s. velocities also reduced. This result gave an agreement with other works (Schwarz *et al.* 1988).

Thirdly, shear stress had a very close relationship with axial velocity and its r.m.s. velocities, these flow parameters determined shear stress distribution downstream of valves. This result agreed with the assumption of the mixing model (Gerhart and Gross, 1985).

Fourthly, maximum shear stress and maximum mean absolute shear stress of the orifice occurred at the same measuring plane within the transition flow region and the position of this region was dependent on the orifice diameter or orifice area.



Figure 5-17. Mean absolute shear stress distribution with axial position

5.3.2 The effects of the orifice shape on shear stress fields

As mentioned in *sub-section 5.2.2*, velocities were measured through four differently shaped orifices with equivalent areas. Fluctuating velocity components of these results were used for calculating shear stresses using *Equation 4-5*.

The maximum shear stress point and maximum mean shear stress of the circular orifice occurred at the 2D downstream measuring plane, whereas those of the triangular, annular and square orifices occurred at the 1D downstream plane. This can be explained by the triangular, annular and square orifices having smaller hydraulic diameters than that of the circular orifice of 12 mm. As can be seen from velocity profiles of the square orifice, the initial jet-flow region just ended at the 1D downstream measuring plane. The triangular and annular orifices had hydraulic diameters of 8.5 and 4.5 mm, respectively. Consequently, plug flow was not observed at 1D downstream and only the second stage flow (fully developed jetflow) was observed in the downstream region of these two orifices. As a result, the maximum shear stress point and maximum mean absolute value for these orifices occurred somewhere less than 1D downstream, so that the shear stress at 1D downstream of the triangular, square and annular orifices was larger than those at 2, 3 and 6D downstream measuring planes.

The triangular orifice produced the highest shear stress and mean absolute value of 230.7 and 104 Pa, respectively. Whereas, the annular orifice with the smallest hydraulic diameter of only 4.5 mm produced the maximum shear stress and mean absolute value of 155 and 90 Pa, respectively. These values were larger than those of the square and circular orifices (for more detail, see *Appendix 4.3*). This result can imply that again *Equation 5-13* is also not valid for calculating hydraulic diameter of annular orifice for shear stresses. The circular orifice generated the lowest shear stress and mean absolute value of 83 and 34.4 Pa, respectively as it had largest hydraulic diameter of four orifices.

As can be seen from these results, the orifice shape (as the valve shape when open) is a very important factor which affects the shear stress fields in the downstream region of valves. Maximum shear stress for the same size of orifice increased dramatically, by 300%, when the orifice shape changed from circular to triangular. This can explain why the shear stress in bioprosthetic heart valve was the highest in comparison with those of other heart valve types (Hanle *et al.* 1989).

Shape	Hydraulic		Axial	1D	2D	3D	6D
	diameter		position				
Triangular	8.5 mm	Maxim	um value	231	133	47	6
		Mean v	alue (Pa)	104	73	17	1.8
Annular	4.5 mm	Maximum value		146	56	33	6
	16	Mean v	alue (Pa)	69	17	13	2.5
Square	10.4 mm	Maxim	um value	130	78	31	5
		Mean v	alue (Pa)	51	35	15	2.2
Circular	12 mm	Maxim	um value	60	83	48	3.5
		Mean v	alue (Pa)	19	34	16	4

Table 5-4. Maximum and mean absolute shear stress at different measuring planes

5.3.3 The effects of the occluder position on shear stress fields

Velocities were measured for three positions of the ball occluder (more details given in *sub-section 5.2.3*). The first position, when the ball was located on the centre line, created two equal areas for forward flow. The second position with the eccentricity of the ball of 1 mm created two unequal areas for forward flow called major and minor orifices. In the third position, due to the ball location being very near to the tube wall, only one major orifice flow was observed.

The 1 mm eccentric orifice generated the highest shear stress and mean absolute value of 185 and 85 Pa, respectively. Whereas the 2 mm eccentric orifice created the lowest shear stress of 138 Pa in comparison with 155 Pa for the 0 mm eccentric and 185 Pa for the 1 mm eccentric orifice (see *Table 5-5*). This result was unexpected and can be explained by the eccentricity of the occluder causing eccentric flow downstream of the orifice, affecting the characteristics of the initial and fully developed jet flow-region. As a result, the initial jet-flow region for differently occluded flows ended at different measuring planes, consequently, maximum shear stress occurred at different planes. For example, the central orifice had two equal areas for forward flow, so that the length of the initial jet-flow region should be

larger than those of the 1 and 2 mm eccentric orifices, and the maximum shear stress should occur at a plane behind 1D downstream. The 2 mm eccentric orifice produced the largest disturbance; as a result, mixing layers of jet and vortex regions merged with each other somewhat quicker to generate fully developed jet-flow, than those of the other two orifices. The transition flow region of the 2 mm eccentric orifice occurred somewhere behind the ball. As a result, shear stress at 1D downstream was not larger than those of the other two orifices, because the maximum shear stress of this orifice should occur somewhere behind the ball at about half D downstream of the orifice. The shear stress profile at 1D downstream of the 2 mm eccentric orifice was already in the fully developed jet flow region. Furthermore, the maximum shear stress of each measuring plane in the fully developed jet flow region reduced from about two to three times when the measuring plane was moved further from the orifice by 1D's distance (see *Tables 5-4* and *5-5*). Maximum shear stress of about 210 Pa for the 2 mm eccentric orifice was expected.

Occluder		Axial	1D	2D	3D	6D
positions		positions				
0 mm	Maximum shear stress		155	55	13	8
	Mean absolute value (Pa)		53	22	6	4
1 mm	Maximum sh	near stress	185	51	25	6
	Mean absolu	te value (Pa)	85	17	12	2.2
2 mm	Maximum sh	near stress	138	43	19	6
5-	Mean absolu	te value (Pa)	58	19	8	3

Table 5-5. Maximum and mean absolute shear stresses at different measuring planes

As can be seen from these results, the larger eccentricities of the occluder caused larger shear stresses (except when very large eccentricity causes one single jet and eliminates the effect of the minor orifice), this can explain why the shear stress for the tilting valve was very high (almost as high as for bioprosthetic valves), even though the tilting valve had larger effective orifice area (Hanle *et al.* 1989), because in the tilting valve, the tilting disc produced eccentric flow and this increased shear stresses. Maximum shear stress and its mean absolute value occurred at different

positions downstream of the orifice dependent on the occluder position and this leads to a conclusion that the comparison of shear stresses at a fixed plane of valves is not fair enough or practical. Like in the pressure drop measurements, the eccentricity of the occluder does not affect as much as the orifice shape and area does.

5.3.4 Summary of flow relationships

The orifice causes stenotic blood flow which leads to two distinct stages of flows downstream of the valve known as initial and fully developed jet flow. These two flow regions produce two corresponding shear stress distributions. Shear stress in the initial region increases when the measuring plane moves further from the orifice and reaches a peak value within the transition flow region. Whereas shear stress in the fully developed jet flow region reduces further from the orifice location. Overall mean absolute shear stress distribution along axial position can be observed in *Figure 5-17*.

Maximum shear stress and its mean absolute value occurs at the same measuring plane - within the transition flow region, and this region is observed at different positions dependent on the orifice hydraulic diameter and occluder position. Smaller hydraulic diameter and larger eccentric orifices produce more disturbed flow, as a result the transition flow region as well as maximum shear stress and its mean absolute value occur at the position closer to the orifice location (see *Figure 5-17* and highlighted data on *Tables 5-4* and *5-5*). This result leads to a conclusion that the comparison of shear stresses of different heart valves at a fixed distance from the valve location in previous studies may lead to mis-evaluating the valve performance.

The magnitude of shear stresses downstream of the valves in each measuring plane is a function of axial velocity profiles and its r.m.s velocities. In the initial jet flow region, minimal and maximal peak shear stresses can be observed in the plug flow region and in the region around the plug flow region, respectively. In the fully developed jet flow region, shear stresses reach peak values where velocities reach peak values (for more detail, see *Appendix 4.2*). These shear stress distributions gave good agreement with Woo *et al.'s* work who measured shear stresses downstream of the Abiomed trileaflet heart valve prosthesis.

As maximum shear stress and its mean absolute value of each orifice occur at the same plane, leading to an ideal that the comparison of heart valve *in-vitro* measurements for maximum mean absolute shear stresses is better than that for maximum shear stresses, because this may reduce measurement error.

The orifice area is the most important factor in reducing shear stresses, but alterations to this are impractical due to the limitation of the valve size and its structure. Changing the orifice shape is a good way to optimise the valve's fluid dynamical performance. The orifice position does not affect shear stress as much as the orifice area and shape do, but this factor can not be neglected.

5.4 The effects of the struts of the ball on velocity and shear stress fields

Two velocity measurement sets were conducted through the annular orifices, the first across the ball and the second across the ball and two struts (see *Figure 5-11 c* and *d*). Because of the presence of these two struts, the velocity profiles at 1, 2 and 3D downstream of the ball were very disturbed and different from those without struts. The velocity profiles at 6D downstream seem to be the same. The velocity profiles without struts got two peak velocities in the regions near to the tube walls corresponding to the centres of two orifice flow areas, and a low velocity region was observed in the centre line of the tube. This distribution of velocities still remained at 3D downstream plane. Whereas, velocity profiles across struts at 1, 2 and 3D downstream planes peaked in the centre of the tube and low velocity regions near to the tube walls. Maximum velocities of 0.37 and 3 m/s were observed at 1D downstream with and without the struts, respectively. The two struts produced two regions of separation and recirculation flow near to the walls of the tube (see *Figure*).

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5-18). These two regions were low velocity and recirculation flow regions and relatively large (6 mm in diameter at 1D downstream position), and they promote the probability of thrombus formation in the regions near to the struts. This observation gave good agreement with Yoganathan et al.'s work (1981) which investigated the caged ball valve. Furthermore, the presence of the two struts produced higher mean tangential velocities and its r.m.s. velocities downstream of the struts than those without struts.

Velocity Profile for case with occluder position 0 mm





Figure 5-18. Velocity profiles with and without struts

The velocity profiles with struts were different from those without struts leading to different shear stress distributions. Shear stress reached a peak value when the velocity profile curve reached its peak maximum or minimum value in the fully developed jet flow region. Shear stress distribution without struts at 1D downstream looked like the shape of fourth order equation, with two positive peak values at the centre of the two jet-flow areas and one negative in the centre line of the tube (for more detail, see Appendix 4.5). A maximum shear stress of 155 Pa was observed at 1D downstream of all two cases, but mean absolute shear stress without struts was larger than that with struts and were 68.7 and 53.4 Pa, respectively (see *Table 5-6*).

As can be seen, the magnitude of the maximum Reynolds shear stress produced by the ball with and without struts was the same, however, the ball with struts produced high velocity gradients near to the tube wall, leading to high wall shear stress which may damage the aorta wall. Furthermore, the ball with struts generated a larger shear stress region (larger mean absolute shear stress) than the ball with struts did. However, the ball with struts produced relatively large stagnation and recirculation flow regions, which are more prone to thrombus formation and tissue overgrowth than areas of high shear stresses (Yoganathan *et al.* 1981).

Occluder		Axial positions	1D	2D	3D	6D
With	Maximum shear stress		155	55	13	8
the struts	Mean absolute value		53	22	6	4
	(Pa)					
Without	Maximu	im shear stress	146	56	33	6
the struts	Mean absolute value		69	17	13	2.5
	(Pa)					

Table 5-6. Shear stress for case of the occluder with and without the struts

5.5 Application to a valve prototype

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Since 1960 more than 50 different cardiac valves have been introduced and most of them have been discarded due to lack of clinical success. The most commonly used basic types are caged ball, tilting disk, bileaflet pivoting disc and tissue bioprosthesis. Different valve types have different occluders and produce different flow patterns in the near vicinity downstream of the valve, though valves have the same size but effective orifice areas are different. Furthermore, the flow pattern depends strongly on the structure of valves such as occluder type, shape and position. For example, the caged disk valve proved the most obstructive of all prosthetic valves and the tilting disk valve produced eccentric flow downstream of the valve and caused high velocity gradient.



Figure 5-19. Jellyfish valve configuration

In this section, experiments were conducted through a heart valve prototype called a Jellyfish valve, under both steady and pulsatile flow conditions. This valve has the size of 20 mm, and is newly and specially designed for VAD. Unlike other mechanical heart valve prostheses, the Jellyfish valve has a very special occluder in the form of a flexible membrane attached to the centre of a stiff stent (see *Figure 5-19*). This causes minimal obstruction and limited occluder inertia, thus leading to small shear stresses, limited pressure gradients and energy losses (Tran *et al.* 1995). This valve was measured and compared to indicate the effects of the occluder on the fluid mechanics of blood flow through the heart valve prosthesis. Furthermore, pressure drops were measured to compare with the results predicted by this study (from the orifice and occluder configuration).

Jellyfish valve measurements were conducted under the same conditions as the orifice measurements. Steady flow pressure drop measurements were carried out with flowrate range 100 to 417×10^{-6} m³/s (6 - 25 l/min). LDA velocity

measurements were conducted under steady flow conditions with a flowrate of 417×10^{-6} m³/s and LDA velocity, flowrate, and pressure drop measurements in pulsatile flow conditions were carried with a cardiac output of 91.7×10^{-6} m³/s (5.5 l/min, peak systolic flowrate is about 417×10^{-6} m³/s), heart beat rate of 1.2 Hz and aortic pressure of 10.26/16 kPa (80/120 mmHg) (see *Figure 3-6* and *3-7*).

5.5.1 The effects of the flexible membrane and orifice shape on steady pressure drops

Steady pressure drops were measured through the Jellyfish valve with and without the flexible membrane as occluder of the valve, at flowrates of 100 to 417×10^{-6} m³/s. *Figure 5-20* shows pressure drops in kPa versus square of flowrates. Data points were on the two distinct straight lines. As can be seen from the results, pressure drops through the valve with the membrane were larger by about 12% than those through the valve without the membrane attached in the centre. This occurred probably because of two reasons:

- the obstruction of the membrane when it opens
- oscillation of the flexible membrane.

The first reason seems to be insignificant, because when the valve was open the flexible membrane contracts into the centre line behind the base where the membrane was attached causing a very small obstruction to the flow downstream of the valve. Furthermore, velocity profiles (see *Figure 5-21*) of 1.5D downstream of the valve with and without membrane were almost the same, and this could imply that the membrane, as occluder, caused minimal obstruction of the forward flow through the Jellyfish valve.

The second reason was surely significant, because when the valve was open, the membrane oscillated and generated a wake downstream of the membrane which produced a disproportionately wide zone of disturbance further downstream. This led to increased pressure drag and consequently to a larger pressure drop across the valve. This result gave good agreement with Tansley *et al.*'s work (1986) when they found the connection between the instability of the ball occluder and pressure drops and tried to reduce the instability of the occluder by modifying inlet and outlet flow area, and Yoganathan *et al.*'s work in 1981 when they investigated the ball valve and measured pressure drops across the valve in steady flow when the ball was tied and untied. Pressure drops across the untied ball valve was larger by about 18% than those across the tied ball valve due to the oscillation of the untied ball downstream of this valve.

The effective orifice area of the Jellyfish valve can be calculated using Gorlin and Gorlin formula (1951) (re: *Equation 4-11*).

The discharge coefficient C for each particular valve or orifice may be derived empirically, this is best done by comparison of the calculated areas with the actually measured areas. For the most cases, C = 1 was considered, the effective orifice area of the Jellyfish valve with membrane was calculated from average value at different flowrates:

 $A_{Effective with membrane} = 2.09$ cm²

In the same way, the average effective orifice area of Jellyfish valve without membrane attached in the centre was calculated:

$$A_{Effective without membrane} = 2.36$$
 cm².

As discussed above, the presence of the membrane gave minimal obstruction to forward flow of the Jellyfish valve, so that the actually measured orifice area of the valve with or without membrane should remain the same and this value is:

$$A_{Actually measured} = 1.74 \text{ cm}^2$$
.

As can be seen from the results of the actually measured and calculated areas, the effective orifice area of the valve with membrane is smaller than that of the valve

without membrane by about 12% due to the oscillation of the membrane in forward flow of the valve. The measured orifice area is too small in comparison with the calculated areas, this is unusual and unexpected, because C factor now is about 1.20, whereas C should be ≤ 1 .



Figure 5-20. Calculated and measured pressure drops versus flowrate squared

Furthermore, pressure drops across the Jellyfish valve were predicted using equations developed in this study. The valve was considered as an annular orifice, so that pressure drops were calculated using *Equation 5-15* considering the shape of the orifice. *Figure 5-20* shows the calculated pressure drops with the measured values versus square of flowrate. As can be seen, the predicted pressure drops stayed within error of 5% in comparison with the results of the valve without membrane and within 15% of the results of the valve with membrane. This means that this formula can be applied and gives good results only for the valve without the oscillation of the occluder. Moreover, actual orifice area of the valve calculated using *Equation 5-17* of this study fitted the measured orifice area with a maximum error of 1.2%.

In conclusion, the flexible membrane as occluder gives minimal obstruction in forward flow through the Jellyfish valve, generating low pressure drops, a maximum pressure drop of 1.33 kPa (10 mmHg) was observed at a flowrate of 417×10^{-6} m³/s (Tran *et al.* 1994). However, the membrane oscillated in the flow and generated a wake downstream of the valve producing larger pressure drops than those of the valve without membrane. Consequently, a smaller effective orifice area was produced. The Gorlin and Gorlin formula is unreliable for the calculation of effective orifice area of the Jellyfish valve, because this formula did not take the shape coefficient of annular orifice flow (the orifice shape) into account. This value for the annular orifice is 1.22 (*Table 5-3*). Now, the calculated area should be:

$$A_{Calculated} = \frac{A_{Effective}}{C_{Shape}} = \frac{2.1}{1.22} = 1.72 \ cm^2$$

This value gives good agreement with the actually measured value and this result can also be calculated using *Equation 5-17* developed in this study, and gives the same result as the *Equation 5-17* took the shape coefficient of the annular orifice into account.

5.5.2 The effects of the flexible membrane on velocity and shear stress fields

Steady velocity measurements were conducted using LDA through the Jellyfish valve, with and without the membrane occluding the valve, at a flowrate of 417×10^{-6} m³/s. Velocities were recorded at 1D up- and 1.5 and 2.5D downstream of the valve. Velocity profiles at 1D upstream, like the velocity profiles of other orifices were relatively unaffected by the presence of the valve or orifice, and in this study they are not discussed. Shear stresses were calculated using *Equation 4-5* from axial and tangential fluctuating velocity components as axial and tangential velocities were measured.

Figure 5-21 shows the comparison of velocity profiles at 1.5 and 2.5D downstream of the valve with and without membrane. At 1.5D downstream, the two velocity

profiles looked almost the same, but the velocity profile of the valve with membrane looked a little bit more disturbed in the left hand side region than that of the valve without membrane. This result implies that the presence of the membrane causes minimal obstruction. However, at 2.5D downstream, the velocity profile of the valve with membrane was different and became flat somewhat quicker than that of the valve without membrane due to the oscillation of the membrane occluder. This result gave an agreement with Yoganathan *et al.*'s, work in 1981 when they investigated velocity fields of the ball valve with tied and untied ball occluder.



Figure 5-21. Velocity profiles with and without the membrane

Velocity profiles of the valve without the membrane were symmetrical and affected by the presence of the base in the centre where the membrane can be attached, as a result, velocities exhibited a low peak value in the center and two high peak value near to the tube walls. Whereas, velocity profiles of the valve with the membrane attached in the centre were asymmetrical, because the Jellyfish membrane was seen to open into an asymmetrical four-lobed configuration (Tran *et al.* 1995).



Figure 5-22. Shear stress fields with and without the membrane

As can be seen from the result of shear stress, the shear stresses of the valve with membrane were larger than those of the valve without membrane. At 1.5D downstream, maximum shear stresses of 41 and 12 Pa were observed in the valve with and without the membrane, respectively. As mentioned above, velocity profiles at 1.5D downstream looked almost the same, but shear stresses were significantly different (see *Figure 5-22*). This can be explained in that the membrane oscillated during the valve opening and generated wake in the flow behind the membrane leading to higher shear stresses. This result agreed with the result of the untied ball

occluder generating larger shear stress than that of the tied ball occluder (Yoganathan *et al.* 1981).

5.5.3 The effects of the occluder type on pulsatile measurements

The potential advantage of this valve for pulsatile flow conditions is limited occluder inertia and therefore reduced regurgitant flow and energy losses (Tran *et al.* 1995). Pressure drops, flowrate and velocities were measured across the valve under pulsatile flow conditions with the valve located in (the in-vitro equivalent of) the aortic position. All tests were conducted at a heart rate of 1.2 Hz (72 beats/min) with aortic pressure set at 10.26/16 kPa (80/120 mmHg) and a cardiac output of 91.7 $\times 10^{-6}$ m³/s (5.5 l/min). Instantaneous velocities, pressure drops and flowrate in pulsatile flow were measured over 8 cycles and then analysed for mean and fluctuating values using a 5° bin analysis (see *section 4.2*) to calculate shear stresses, regurgitant flow and energy losses.

Velocities under pulsatile flow conditions were recorded at several positions such as 1D upstream and 1, 1.25, 1.5 and 2D downstream over 8 cycles. Firstly, data was analysed for mean and fluctuating components using *Equation 4-6*, then shear stresses were calculated using *Equation 4-5*. As in steady flow, the maximum shear stress region in pulsatile flow occurred in the near vicinity downstream of the valve, with a maximum shear stress value of 90 Pa near to the same point where it occurred in steady flow. This value is sub-critical for haemolytic damage in comparison with the threshold value of 150 Pa.

Figure 5-23 shows velocity and shear stress of a maximum shear stress point at 1D downstream measuring plane versus a period of systolic time. The magnitude of shear stresses was strongly dependent on the time during systole, and had its peak value near to the peak velocity of that point during systole. This result agreed with other results of previous investigators eg. Woo *et al.* (1983). The peak shear stress value lagged behind the peak velocity value (see *Figure 5-23*), this may be due to the

effect of the oscillation of the flexible membrane; when the velocity has reached its peak value and started reducing, the membrane became most unstable and this produced the greatest wake during systole. Consequently, shear stresses at that time were shown to be highest.

Pulsatile pressure drops and flowrate were recorded over 8. Again, these data were analysed using the 5° binning technique (*Equation 4-6*) for mean values and these values were plotted over a cardiac cycle (see *Figure 5-24*). Pressure drops were the difference between pressures in the up- and downstream regions of the valve, and maximum pressure drop of 6 kPa (45 mmHg) was observed. This value was larger than the maximum value generated in steady flow due to the acceleration of pulsatile flow.



Figure 5-23. Flowrate and shear stress over a cyclic period

Regurgitant flow consisted of the reverse flow when the valve was closing and the leakage when the was closed. Total flow volume was the integral of flowrate over a complete cycle and regurgitant flow volume was integrated over the two stages of the cardiac cycle using *Equations 4-14* and 4-12, respectively. The ratio of the regurgitant volume to total volume of the jellyfish valve over a cardiac cycle was about 4% in comparison with about 8-12 % and 1-4% of other mechanical and trileaflet bioprosthetic heart valves, respectively (Woo *et al.* 1983 and Tillman *et al.* 1984). It means that regurgitant flow of the Jellyfish heart valve was small in comparison with those of other mechanical heart valves in the literature. This can imply that tissue and membrane occluders are a major factors in reducing regurgitant flow and energy losses.



Figure 5-24. Pressure drop and flowrate over a cycle

Energy loss is the product of pressure drops and flowrate (see Equation 4-16), it is lost in three distinct stages; (T_1) resistance of forward flow during systole; (T_2) reverse flow during closing and (T_3) leakage flow during closed phase (Teijeira and Mikhail 1992).

Energy loss of the Jellyfish valve was calculated using Equations 4-16 and 4-17 from the pressure drop and flowrate data analysed by the 5° binning analysis. It was found that energy losses of this valve were very limited (3.5%) in comparison with those of other heart valves (6-10%) eg. the ball valves, tilting valves and St. Jude Medical valves (Teijeira and Mikhail 1992). This was interesting in that the energy loss of the first stage (resistance of forward flow during systole) in other mechanical heart valves was about 50% (40 - 60%) of the total energy losses (Teijeira and Mikhail 1992). On the other hand, in the Jellyfish valve energy loss generated by the resistance of the occluder in the first stage flow was almost zero. This was probably due to the fact that the flexible membrane occluder of the valve had little inertia - hence produced minimal resistance for forward flow of the valve.

5.5.4 Summary of Jellyfish valve flow

The membrane of the Jellyfish valve oscillated and generated wake downstream of the valve when the valve was open. The oscillation of the membrane affected pressure drops, shear stress and velocity fields eg. increased pressure drops by 12%, maximum shear stresses and mean absolute shear stresses by about 400% (from 15 to 58 Pa and from 12 to 41 Pa, respectively). However, velocity profiles became flat somewhat quicker than those of the valve without membrane, but the presence of the membrane produced a region of stagnation and recirculation of 5 mm in the centre and at 1D downstream of the valve. This may lead to thrombus formation and tissue overgrowth in the near vicinity downstream of the valve (Tran *et al.* 1995).

Though the presence of the flexible membrane caused more disturbance, larger shear stress and pressure drops, these values were relatively smaller than those of other heart valves, and shear stresses were shown to be sub-critical for haemolysis. The use of the flexible membrane occluder could lead to some advantages over other occluder types:

- The membrane produces minimal flow obstruction hence relatively low shear stresses and pressure gradients.
- The oscillation of the membrane does not effect shear stresses and pressure gradients as much as the orifice area does - hence these values were smaller than those of other heart valves.
- The oscillation of the membrane also reduces the extent of the stagnation and recirculation region and makes the velocity field become redeveloped quicker.
- This causes limited occluder inertia and therefore reduced regurgitant flow in forward flow stage, and energy losses in forward flow and closing stage.

Performance of the Jellyfish valve could be predicted well from the relationships for occluder and orifice flow developed earlier in this chapter.

This chapter draws conclusions about two major aspects of this research work, viz: the experimental techniques used, verification of the techniques and justification of selection of the techniques, and also the results gleaned from this study, critique of these results and their significance to the analysis of heart valve fluid mechanics.

6.1 Verification of Experimental Techniques

Flow through a series of orifices and a prototype heart valve prosthesis have been studied in some detail.

Pressure drop across, velocity, shear stress and turbulence measurements in different orifices and a prototype heart valve prosthesis (called the Jellyfish valve) can provide quantitative descriptions of steady flow characteristics of the region downstream of prosthetic heart valves.

Pressure drop measurements were analysed to develop empirical relationships between flow parameters for flow through heart valve prostheses with the aid of dimensional analysis techniques. These techniques can reduce the complexity of experimental programmes and at the same time increase the generality of experimental information. Static pressure distributions along the wall, downstream of the orifice plane, were not produced, as only one downstream pressure-tap plane was used; this was located 6 diameters downstream of the orifice plane.

Turbulence intensity and Reynolds stresses were obtained from LDA velocity measurements. Results gained by LDA such as velocity profile, shear stress, turbulence intensity and velocity fluctuation distributions in the upstream region of fully developed turbulent flow give good agreement with Longwell's work (1966) adding credibility to measurements taken downstream of the orifice plane.

Moreover, mean axial velocity and shear stress distributions downstream of the orifice agree with the theory of turbulent jet flow (Abramovich 1967) and Woo *et al.*'s work (1983), respectively. Measured velocity profiles and shear stresses accorded well with classical turbulent jet theory and good correlation was established between observed pressure gradients, shear stresses and velocity profiles in the flow regions just downstream of orifices and occluders. These findings were used to predict flow properties of a developmental heart valve - there was good agreement between these predictions and measured flow patterns.

Velocity and shear stress profiles gained by LDA were sparse and a full picture of the flow downstream of valves was not possible due to a limited number of measuring planes, but were adequate for the purposes of this study. LDA signals near to the tube walls were very noisy reducing the accuracy of measurements and precluding measurements in the region near to the orifice due to the obstruction of the test section wall caused by the valve or orifice insertion. Furthermore, the difference of the two measurement volume locations, caused by the refractive effects of the curved window through which the laser beams were passed compelled the use of error minimisation techniques to be applied to shear stress results.

The experimental methods adopted exhibited advantages in investigating heart valve flow over other methods, eg. CFD. This was especially so, in evaluating the effects of the occluder, the occluder oscillation, and the presence of the struts on turbulent flow phenomena of valves. The oscillation of the flexible membranous occluder of the Jellyfish valve increased pressure drops and shear stresses and the presence of the struts produced a large stagnation and recirculation region in good agreement with Yoganathan *et al.*'s work (1981). However this occluder motion highlighted the shortcomings of the Gorlin and Gorlin analysis and was a good vehicle for demonstrating the advantages of the orifice area estimation techniques developed in this study.

6.2 **Results from this study**

Results of this study can provide some clinical significance for further valve design and investigation as follows:

Pressure drops are compared for prosthetic heart valves by simply measuring the geometries of valves using *Equation 5-15* (which was derived from results from the present study):

$$C_{P} = \frac{C_{Pr} \times C_{PR} \times C_{PE}}{29.21423} \times \Phi_{Shape}$$

where:

 $C_{PR} = 0.473249 + 270.05902 e^{\frac{A}{0.10002386}}$ $C_{PR} = 5.294376 + 10.382888 e^{\frac{-Re}{3302.9157}}$ $C_{PE} = 5.371233 + 0.004281 \times E^{2}$ $\Phi_{Shape} \text{ is the shape factor}$ $r_{A} \qquad \text{is the ratio of orifice area to tube or sewing ring area}$ $Re \qquad \text{is Reynolds number}$ $E \qquad \text{Eccentricity stated as a percentage.}$

This procedure can reduce the need to measure pressure drops across valves and produce results which are unaffected by measurement error caused by the flow channel, pressure tap locations, etc.

An Equation (5-17) for calculating actual valve orifice area:

$$A_{Real} = \frac{A_{Effective}}{C_{Position} \times C_{Shape}}$$

where

$$A_{Effective} = \frac{Q}{44.5 \times \sqrt{\Delta P}}$$

Q

is flowrate

ΔP	is the pressure drop through the valve
C _{Position}	is a position coefficient
C _{Shape}	is a shape coefficient

may assist cardiac surgeons in the selection of suitable valve size for implantation into individual patients.

- Pressure drop measurements across prosthetic heart valves are necessary, but do not provide enough information for valve assessments and comparisons.
- LDA velocity measurements are able to assess two important factors in heart valve investigations, namely axial velocity profiles and shear stress fields. Axial velocity profiles are the dominant factor in heart valve flow over other velocity profiles eg. tangential and radial as these axial velocity profiles provide information about the regions of stagnation and recirculation which promote thrombus formation and tissue overgrowth.
- Axial velocity profiles can also identify the region where maximum shear stress occurs. Furthermore, high axial velocity gradients produce high shear stress giving good agreements with Hanle *et al.*'s work (1989).
- The flow downstream of orifices or valves is jet flow, it consists of three stages: initial jet flow region, fully developed jet flow and finally, redeveloped turbulent flow. In the first stage, plug flow can be observed and the length of the initial jet flow region is about 2d, where d is hydraulic diameter of orifices. Initial regions of annular and triangular orifice flow were not observed in these results, because the first velocity profile downstream of the orifice is located at the position of 1D (19 mm) larger than 2d. The second stage is fully developed jet flow, where plug flow disappears and mean velocity gradients become smaller getting further from the orifice location. Except for the concentric annular orifice, the length of the second stage flow depends inversely on hydraulic diameter of primary orifices. The region between the end of the initial jet flow and the beginning of the second stage is called a transition region. At the end of the second stage, the flow again becomes plug at about 3 to 7D downstream of the

orifice dependent on the hydraulic diameter and the orifice and occluder position where velocity profiles are flat across the entire tube diameter. Beyond this point the flow pattern becomes redeveloped turbulent tube flow and this stage is called the third stage.

- Theory indicates that three flow stages should be observable downstream of the orifices. However, these three stages of heart valves, especially the initial jet flow region, were hardly observed. This was because the length of the initial flow region (2d of valve) ended before the first measuring plane location; also the presence of the valve elements eg. occluder, struts and hinge make the flow more disturbed and patterns more difficult to recognize. The length of each stage flow for the different orifices commenced and ended at different positions downstream of their location. This leads to a conclusion that the comparison of velocity profiles of heart valves, used in previous heart valve studies may lead to comparisons being made of shear stresses between different heart valve types.
- The orifice area is the most important factor in the causation of shear stress, pressure drops and the extent of stagnation and recirculation regions.
- The valve can be optimised by increasing the ratio of orifice area to sewing area (r_A) : the result of this study shows that as r_A increases from 0.4 to 0.75, pressure drop and shear stress reduces 10 and 70 fold, respectively. However, it is often infeasible to increase r_A due to the limitation of the valve size and sewing ring requirements: hence r_A must be optimised, whilst maintaining flow area, by adapting the orifice shape and the occluder type and position.
- The orifice shape of the valve when the valve is fully open is the second most important factor in the causation of shear stress and pressure drops. Pressure drops and shear stress at flowrate of 417×10⁻⁶ m³/s (25 l/min) change 140% and 300%, respectively when the orifice shape changes from circular triangular. This can explain why pressure drops and shear stresses in

bioprosthetic heart valves were highest in comparison with those of other heart valve types of the same size (Hanle *et al.* 1989), as bioprosthetic valves produce a triangular orifice shape when open.

- The eccentricity of the orifice or occluder does not affect pressure drops and shear stresses as much as the orifice area and shape do. However, the eccentricity of the occluder introduces the largest effects on the causation of stagnation and recirculation regions downstream of valves.
- Two flow regions, initial and fully developed jet flow, downstream of the orifices produce two different shear stress distributions implying that axial velocities are dominant over tangential and radial velocities in determining shear stresses. This gives good agreements with other works (Longwell 1966; Tennekes and Lumley 1972; and Gerhart and Gross 1985).
- The comparison of maximum shear stress values produced by each valve sometimes may lead to mis-understanding of valve performance due to the error of measurements, especially shear stress measurements. In order to avoid this problem, mean absolute shear stress of each measuring plane is introduced.
- Maximum turbulent shear stresses along radial positions occur in the region of the sharp axial velocity gradients. Along axial positions maximum turbulent shear stresses depend on the flow region downstream of the orifice. This result gives good agreement with Schwarz *et al.*'s work (1988). Maximum shear stress value and maximum mean absolute shear stress of a measuring plane occur at the same position within the transition flow region downstream of the orifices.

6.3 **Recommendations**

The recommendations of this study are as follows:

- In order to acquire better heart valve haemodynamic performance, new heart valve designs should have (a) a large ratio of orifice area to sewing ring area, (b) circular orifice shape, (c) a non-central occluder and (d) concentric orifice flow.
- The comparison of maximum velocity gradient and shear stress in heart valve prostheses at a fixed position is not practical. Mean absolute shear stress should be compared within the transition flow region of the valves.
- The use of the flexible membrane as an occluder of valves is promising for future valve design, as this occluder type causes minimal obstruction (maximal orifice area); even though the oscillation of the membrane produces higher pressure drops and shear stresses. However, these values are still smaller than those of other heart valve types, because the orifice area is the most important factor effecting flow parameters. The material of the membrane should be durable and not easily torn under pulsatile flow.
- LDA is a powerful technique for investigating fluid flow of prosthetic heart valves. In order to acquire more accurate and reliable results, especially shear stresses, a larger laser beam intersection angle should be applied producing smaller measurement volume length and reducing the effects of curved windows on the location of the measurement volume. Furthermore, the difference in location (or lack of spatial coincidence) of the two measurement volume locations can be reduced by reducing the refractive index of the tube making the test section wall's refractive index as close to the refractive index of the test section liquid as possible and by reducing wall thickness.

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8.2 Appendix two

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Haemodynamics of a Jellyfish heart valve

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HAEMODYNAMICS OF A JELLYFISH HEART VALVE

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Introduction All prosthetic heart vales exhibit haemodynamic inadequacies in that they are liab to thrombus formation, tissue overgrowth, haemolysis, etc. This work examines a new artifici heart valve viz the Jellyfish valve designed by Professor Umezu of Waseda University as Professor Imachi of The University of Tokyo. This study aims to provide haemodynam information about this newly designed valve and to give an indicator of dysfunction potentials f this prosthesis through the determination of velocity profiles, shear stresses and pressure drops.

Methods Steady and pulsatile-flow experiments were conducted to examine the fluid flow régin through the Jellyfish artificial heart valve using Laser Doppler Anemometry (LDA). The LD technique has become the most popular method in recent years for the determination of she phenomena in flow through heart valve prostheses. A two component Laser Doppl Anemometer was used to determine the velocity and turbulence parameters of inlet flow and flo downstream of the valve; these along with the pressure drops across the valve were compare those of other valves.

Results Pressure drops across the valve compared favourably with those of other heart valve (>10 mmHg), and the Jellyfish valve was shown to exhibit sub-critical values of shear stress >150 Pa, see figure 2); but a large stagnation region was exhibited immediately downstream



Radial Position (mm)

Figure 1. Steady-flow velocity profiles downstream of the valve



Figure 2. Turbulent shear stresses upstream and downstream of the valve

of the valve (see figure 1) - this could have implications for excessive thrombus formation an tissue overgrowth.

These preliminary studies show that the Jellyfish valve exhibits good flui Conclusions dynamical properties, though possible thrombogenisity of the valve needs further investigation.

Tran, V.V., Tansley, G.D., Morsi, Y.S. and Larson, C.M., 1995.

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Proceedings of The Sixth Asian Congress Of Fluid Mechanics. May 22-26, 1995, Singapore, 1030-1034.

THE SIXTH ASIAN CONGRESS OF FLUID MECHANICS May 22-26, 1995, Singapore

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LDA EVALUATION OF A PROTOTYPE JELLYFISH ARTIFICIAL HEART VALVE

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ABSTRACT Experiments were conducted under steady flow conditions to examine the fluid flow régime through a prototype Jellyfish artificial heart valve. A two component Laser Doppler Anemometer (LDA) was used to determine the velocity and turbulence parameters of flow at inlet and downstream of the valve. The velocity profiles and turbulence shear stress parameters are presented and compared with critical threshold values for blood trauma. The Jellyfish valve was shown to exhibit sub-critical values of shear stress and very limited jetting under steady flow conditions.

1. Introduction

Contemporary Total Artificial Hearts (TAH's) and Ventricular Assist Devices (VAD's) rely on passive non-return valves for the control of flow direction; but most mechanical valves exhibit less than optimal performance in that they present ring thrombus (clotting near the valve/seat interface due to flow disturbances near abrupt surface discontinuities), regurgitant flow due to inertial properties of the occluder, haemolysis (the destruction of red cells under high shear stresses), and in rare cases, mechanical failure due to water hammer and erosion.

- Many centres around the world are researching ways of improving heart valve design through a re-examination of the fluid dynamics of these devices. Of particular influence are the magnitudes of shear stress and shear rate developed in the vicinity of heart valves; these parameters are commonly measured with Laser Doppler Anemometers (LDA) or are predicted using Computational Fluid Dynamics (CFD). Both of these techniques have been instrumental in the quantum leaps forward made recently in fluid dynamics. As a result of such developments, a number of new valve design concepts are now being examined by many researchers world wide. Flow phenomena of particular interest are:

- shear stresses a threshold level of Reynolds stress for haemolysis in a free jet is around 400 500 N/m² [1,2], though blood trauma is both time and stress dependent and damage can occur at values as low as 150 N/m² close to a prosthetic surface [2],
- velocity profile shear stresses developed in impingent jets are very high. Jets forming downstream of an artificial heart valve are deleterious to a valve's proper functioning,
- shear rate low shear rates exacerbate thrombus formation [3] and can lead to valve dysfunction or embolism.

There is a healthy volume of literature which reports fluid dynamical studies of heart valves, e.g.: Yoganathan *et al.* reported on studies of Björk-Shiley[4] and Starr-Edwards [5]valves, Tillman *et al.* [6], using flush mounted shear stress probes examined three different types of mechanical valves and found a peak value of 120 - 140 N/m² at the large orifice of a

Björk-Shiley valve, 12-15 N/m^2 at the large orifice of a Lillehei-Kaster valve and 85 N/m^2 at the valve ring of a Starr-Edwards valve.

In this study a new type of valve known as a Jellyfish valve - which was developed by Professor Imachi at the University of Tokyo - is being examined by groups at Adelaide, Flinders and Swinburne Universities.

The Jellyfish valve is unique in design; incorporating a thin flexible membranous occluder attached centrally to a rigid frame. The potential advantages this valve could offer are:

- minimal flow disturbance hence relatively low shear stresses and pressure gradients,
- limited occluder inertia and therefore reduced regurgitant flow,



Figure 1 Jellyfish valve and measurement planes

 reduced cost - this is important, since the cost of valves is a significant proportion of the total cost of VAD's and TAH's.

2. Experimental Facilities

Steady flow LDA measurements were carried out in Adelaide using the 488 nm and 514.5 nm beams from a 5 Watt Spectra Physics 165 argon-Ion laser driving a TSI 9100-7 Laser Doppler Anemometer. Optics included two Bragg cells, a beam expander (to 82.5 mm beam spacing) and a 450 mm lens mounted on TSI 9400 traverse. Steady flow generated by a small centrifugal pump circulated through a size 20 Jellyfish valve⁺ and was returned, via a turbine flow-meter to an open sump. Experiments with a flow rate of 10.7 - 10.9 l/min are reported here. The valve was inserted into a plane acrylic tube (refractive index 1.48 and internal diameter 19 mm) which was then placed in an index matching enclosure filled with medical grade paraffin. The LDA seeding particles used were 11 µm metallic coated spheres.

Two velocity components (v_z and v_{Θ}) and stress measurements were recorded at two planes upstream of the valve, at 1 diameter (19 mm) and 2 diameters (38 mm) upstream of the valve seating ring, and at five positions downstream of the valve, at 1, 11/4, 11/2, 2 and 3 diameters downstream of the seating ring, providing a good picture of the structure and subsequent development of the flow (see Figure 1). Measurements were made in cross sectional planes in 1 mm increments across the radius of the test section at each of the above

^{*} The outer diameter of the valve ring was 20 mm, the inner diameter was 18mm

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planes. Between 15-18 of these sites per plane yielded valid data - data was not always available near to the tube walls or near to the Jellyfish membrane. Index matching between the flowing liquid and the test cell was not carried out limiting measurements to the axial (z) and tangential (θ) directions. Some difficulties were encountered due to the use of acrylic which is highly absorbent around the 500 μ m wavelength.

3. Data Analysis

Reynolds shear stresses are calculated from 1024 coincident data points collected in each of the two directions as:

$$\tau_{R} = \frac{1}{K} \sum_{i=1}^{K} \nu_{z}^{\prime} \nu_{\theta}^{\prime} = \overline{\nu_{z}^{\prime} \nu_{\theta}^{\prime}} = \overline{\nu_{z} \nu_{\theta}} - \overline{\nu_{z} \nu_{\theta}}$$
(1)

where

$$v = \overline{v} + v',$$
 $\overline{v} = \sum_{i=1}^{K} \frac{v}{K}$

4. Results and Discussion

Under steady-flow conditions, the Jellyfish membrane was seen to open into an asymmetric four-lobed configuration; measurement planes were orientated such that they either dissected the lobes or passed between the lobes. Velocity profiles are depicted in





Figure 3 Velocity profile dissecting lobes

Figures 2 and 3 for both of these measurement orientations; each shows a series of velocity profiles for successive steps downstream of the valve. The plots reveal areas subjected to annular jetting and regions of pronounced flow reversals at 1 diameter downstream which gradually decays until the velocity profile is almost flat 3 diameters downstream. Maximum flow velocities are evident at a 5 mm radial location in both the between lobes measurements (0.968 m/s) and dissecting lobe measurements (0.897 m/s).

Figures 4 and 5 show the shear stress profiles in the series of measurement planes downstream of the valve; again measurements between the lobes and dissecting the lobes are indicated. Reynolds shear. stress values were calculated using equation 1.



Figure 4 Shear stress profiles between lobes Figure 5 Shear stress profiles dissecting lobes

5. Conclusion

LDA has been used to determine the fluid flow and turbulence parameters inside an artificial heart valve. It was found that the magnitude of shear stresses were of the order of $1-14 \text{ N/m}^2$ which is sub-critical for haemolytic damage. Velocity profiles downstream of the valve show only limited jetting - restricting shear stress development at the flow vessel wall (where haemolysis is exacerbated and where endothelial damage would occur if the valve were placed into a natural aorta). Regions close to the valve (in the central recirculation region and near the valve ring) are the most likely regions to display thrombosis; these were not examined during this study due to difficulties of (control volume) access. Since turbulence in the valve is anisotropic, shear stresses calculated from v_0 and v_r' will be of a greater magnitude.

6. References

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Nomenclature

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V _z	mean velocity along the flow axis (z)
V,	mean velocity in the radial direction
V _e	mean velocity in the tangential direction
v_z, v_p, v_{Θ}	local instantaneous velocity components
$v_z v_{\Theta}$	mean product of v_z and v_{Θ}
v_z', v_{Θ}'	fluctuations about the local v_z and v_{Θ} components of velocity
σ _z	standard deviation of the v_{z} component
τ _R	Reynolds Shear Stress
T	coincident time window
Κ	number of samples in a record

8

8.3 Appendix three: Pressure drop measurements

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PRESSURE DROPS - RAW DATA

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1. Measured and calculated pressure drops across different orifices

P are pressure drops in mm Hg, eg. P(d12) are pressure drops across 12 mm diameter onlice d is the orifice diameter in mm

Annular, square and triangular are different shaped orifices with equivalent area of the 12 mm circular orifice. Measured

l/min	P(d16.5)	P(d15)	P(d13.5)	P(d12)	P(d10.4)	P(Annular	P(Square)	P(Triangular)	
24.25	4.2	7.8	18.6	40.6		30	51.5	55.6	
21	3.3	6.4	14.1	30.8	80.6	22.4	39.2	42.7	
18	2.6	4.7	10.3	22.4	59.3	16.4	28.7	31.5	
15	2	3.4	7.1	15.4	40.9	11.9	20.2	21.7	
12	1.5	2.4	4.8	10	26.4	7.8	13.1	14.1	
9	1	1.7	3.1	6.2	15.1	4.8	8	8.4	
6	0.6	1.2	1.6	3.1	7.1	2.5	3.9	4.4	
Calculated	t								
l/min	P(d16.5)	P(d15)	P(d13.5)	P(d12)	P(d10.4)	P(Annular	P(Square)	P(Triangular)	
24.25	4.602302	7.527849	16.66459	40.99515		30.99233	52.67877	57.14724	
21	3.455065	5.651347	12.51053	30.7761	78.94001	23.26673	39.54729	42.90189	
18	2.545595	4.163755	9.217408	22.67497	58,1608	17.14228	29.13734	31.60891	
15	1.781533	2.914002	6.450798	15.86907	40.7038	11.99701	20.39175	22.12148	
12	1.164478	1.904703	4.216488	10.37263	26.60556	7.841708	13,32883	14.45945	
9	0.69273	1.133078	2.508324	6.170517	15.82724	4.664911	7.929114	8.601701	
6	0.354127	0.579234	1.282265	3.154393	8.090948	2.384721	4.053396	4.397224	
Maximum error of 1.94 mmHg									
2. Pressure drops across a circular orifice of 12 mm diameter at various eccentricities.									
P are pressure drops in mm Hg, eq, P(e=1) are pressure drops across the orifice mounted at 1mm eccentricity									
e is the eccentricity in mm									
· · · · ·									

Measured								
l/min	P(e=0)	P(e=0.5)	P(e=1)	P(e=1.5)	P(e=2)	P(e=2.5)	P(e=3)	P(e=3.5)
24.25	40.6	41	41.7	42.9	44.1	45.9	47.9	50.6
21	30.8	31.2	31.8	32.8	33.8	34.9	36.8	38.9
18	22.4	22.6	22.9	23.8	24.9	25.6	27.1	28.6
15	15.4	15.9	16	16.4	17	17.9	18.5	19.8
12	10	10.3	10.5	10.9	11.1	11.6	12.3	13.3
9	6.2	6.4	6.5	6.6	6.7	6.9	7.3	7.7
6	3.1	3.2	3.4	3.4	3.4	3.4	3.5	3.8
Calculated	ł							
l/min	P(e=0)	P(e=0.5)	P(e=1)	P(e=1.5)	P(e=2)	P(e=2.5)	P(e=3)	P(e=3.5)
24.25	41.07	41.29642	41.97567	43.11033	44.69955	46.73902	49.23132	52.17645
21	30.8323	31.00227	31.5122	32.36402	33.55709	35.08817	36,9592	39.17019
18	22.71638	22.84161	23.21731	23.84491	24.72393	25.85199	27.23051	28.8595
15	15.89804	15.98569	16.24862	16.68785	17.30303	18.0925	19.05726	20.19731
	40 20157	10 44996	10 62072	10 90782	11.30992	11.82595	12.45655	13.20173
12	10.39137	10.44000	10.02.012					
12	6,181784	6.215864	6.318103	6.488891	6.728097	7.035074	7.410211	7.853507
12 9 6	6.181784 3.160153	6.215864	6.318103	6.488891 3.317147	6.728097 3.439431	7.035074 3.596359	7.410211 3.78813	7.853507 4.014745

3. Measured and calculated pressure drops across a ball occluder with various eccentricities. P are pressure drops in mm Hg

e is the eccentricity, eg. e=1 means 1 mm eccentricity

Meas

Measured					
l/min	Pe=0	Pe=0.5	Pe=1	Pe=1.5	Pe=2
24.25	30	31.6	31.7	32.7	34.5
21	22.4	23.1	23.7	24.2	25.7
18	16.4	17.1	17.4	17.7	18.9
15	11.9	12.2	12.4	12.6	13.4
12	7.8	8.3	8.5	8.5	9
9	4.8	4.9	5.1	5.3	5.5
6	2.5	2.5	2.6	2.7	2.8
Calculated	đ				
1/min	Pe=0	Pe=0.5	Pe=1	Pe=1.5	Pe=2
24.25	30.99233	31.28635	32.16736	33.63588	35.69174
21	23.26673	23.48745	24.14885	25.25131	26.7947
18	17.14228	17.3049	17.7922	18.60446	19.74159
15	11.99701	12.11083	12.45186	13.02032	13.81614
12	7.841708	7.916099	8.139014	8.51058	9.030756
9	4.664911	4.709165	4.841773	5.062812	5.372257
6	2.384721	2.407344	2.475134	2.58813	2.74632
			Maximum	error of 1.2	mm Hg

8.4 Appendix four: LDA velocity data

Notations:

2 1 1

X:	Axial position (tube diameter)
Y:	Radial position (mm)
U MEAN:	Axial mean velocity (m/s)
U RMS:	R.M.S. axial velocity (m/s)
U TURBU:	Axial turbulence intensity
W MEAN:	Tangential mean velocity (m/s)
W RMS:	R.M.S. tangential velocity (m/s)
W TURBU:	Tangential turbulence intensity
uw:	Product of axial and tangential fluctuating velocities (m^2/s^2)

A. 4.1. Typical velocity profile in upstream region

VELOCITY IN UPSTREAM REGION X: Axlal position Y: Radial position (mm)

x –	Y		U MEAN	URMS	U TURBU	W MEAN	W RMS	W TURBU	uw
1D up-		1	1.173449	0.208232	17.74529	-0.01265	0.005137	0.437809	-0.00013
stream		2	1.374797	0.13997	10.18113	-0.01254	0.005699	0.414549	-0.00034
		3	1.458564	0.120613	8.269293	-0.01349	0.005449	0.373605	-0.00031
		4	1.543701	0.107682	6.975562	-0.01787	0.022098	1.431471	-0.00029
		5	1.640309	0.086948	5.300682	-0.03272	0.07275	4.435137	-0.00023
		6	1.679676	0.069232	4.121766	-0.01654	0.055096	3.280159	-0.00013
		7	1.719911	0.052917	3.076706	-0.0167	0.044466	2.585346	0.000159
		8	1.727269	0.048163	2.788378	-0.01446	0.035814	2.07342	-0.00008
		9	1.720813	0.048876	2.84028	-0.01467	0.034408	1.99954	0.000006
		10	1.706575	0.055046	3.225533	-0.01245	0.036691	2.149955	0.000286
		11	1.68486	0.061981	3.678728	-0.00833	0.042187	2.503902	0.00036
		12	1.657942	0.068716	4.14467	-0.00806	0.047046	2.837627	0.000466
		13	1.623301	0.077202	4.75584	-0.0097	0.053601	3.301968	0.000758
		14	1.575847	0.090397	5.736437	-0.00944	0.064365	5 4.084487	0.000835
		15	1.495926	0.109244	7.302743	-0.00054	0.073803	4.933569	0.000857
		16	1.397421	0.120975	5 8.657001	0.00433	0.085848	6.143296	0.000698
		17	1.275121	0.156962	12.30961	0.003873	0.096953	3 7.603453	0.00055
		18	1.024328	0.282222	7 27.55242	-0.003	0.098037	9.570908	0.000578









A. 4.2. Velocity data across circular orifices

SHEAR STRESS AND TURBULENCE INTENSITY IN 12 mm CIRCULAR ORIFICE



VELOCITY RAW DATA - CIRCULAR ORIFICE OF 12 mm DIAMETER


VELOCITY RAW DATA - CIRCULAR ORIFICE OF 13.5 mm DIAMETER



14 16 18 Radial (mm)

14 16 Radial (mm)

14 16 18 Radial (mm)

> 4 16 18 Radial (mm)

SHEAR STRESS AND TURBULENCE INTENSITY IN 13.5 mm DIAMETER CIRCULAR ORIFICE







SHEAR STRESS AND TURBULENCE INTENSITY IN 15 mm DIAMETER CIRCULAR ORIFICE

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VELOCITY RAW DATA - CIRCULAR ORIFICE OF 16.5 mm DIAMETER







A. 4.3. Velocity data across different shape orifices

VELOCITY RAW DATA - CIRCULAR ORIFICE OF 12 mm DIAMETER



SHEAR STRESS AND TURBULENCE INTENSITY IN 12 mm CIRCULAR ORIFICE



VELOCITY RAW DATA - CONCENTRIC ANNULAR ORIFICE

X D	U I	MEAN	URMS	U LUKBU 1	MMEAN V	AKW2 A	TURBU W				0 1		maula	1 walo	alm.	
1D dow	1 -	0 17763	0.546149	307,4663	-0 09059	0_062871	35 3948	-0.0018		3	D dow	nstream	ofile	1 4610	city	2- L
stream	2 -	0.09713	0.540223	556 1886	-0 03758	0.066871	68 84695 -	0.00066	^{2.5} T m	/s		pro	01110			1
	3 -	0.04198	0.58049	1382,839	-0.02329	0,123628	294 5047	-0.0054	2 +	-						
	4 0	162122	0,593131	365 8553	-0 04155	0 413768	255.2205 -	0.01104	16							
	5 0	261599	0.59163	226 1597	-0 05407	0 531864	203.3129 -	0.03875	1.5							
	6 C	.366684	0,594241	162,0581	-0 16807	0 547002	149 1753	-0.07313	1 +			- 중 - 등	8.			
	7	0.34688	0.61817	177_1871	-0.25244	0.591151	169.4424	-0.09918	051	-				٩.,	, F	Radial (mm)
	8 0	.344105	0,653481	189,9075	-0 35448	0 618844	179.8416	-0.13521	0.0	-		-01-01-	The.		B-R	
	9 (242036	0.66919	276,4838	-0.3792	0_649657	268.4132	-0.15509	0	- ar	T I	-	-	-		R. R. R.
	10 0	0.107388	0.650112	605,3869	-0 34475	0 648602	603.9808	-0.14986	-0.5 0	2	1		-10	12	10- FF	16 18
	11 0	018675	0.640627	3430,429	-0.28789	0.620767	3324.08	-0.11728		8-8-8				1 B.	10-10-	8-0
	12	-0.15028	0.582681	387,7362	-0.08574	0.606888	403.8445	-0.07168	-1:+							
	13	-0.285	0.535999	188.0683	0 057775	0_564718	198.1451	-0.03566	-1.5 L							
	14	-0 34829	0.529583	152.054	0.127928	0.523177	150,2148	0.00592								
	46	-0 47239	0 461189	97 62959	0.106085	0.487478	103.1948	0.028103 🖵		_			_			
	16	-0 57648	0 454433	78.82864	0.010319	0.466895	80,9903	0.018806								
	47	-0.6085/	в п 427639	61 2156	-0.00558	0.403158	57.71122	0.007521								
	49	-0.7657	4 0.37676	1 49 20232	-0.01289	0.379178	49.51797	0.006417								
~ -	- 10 1	I MEAN	11 RMS	U TURBU	W MEAN	WRMS	W TURBU	W		_			_			
20 dout	, u	0 76700	A 0 43478	6 56 6211	-0 03393	0.020754	2,705893	0.000226		2D c	lownstr	eam a	xial ve	locity	profil	e
20 dow	-	0.09455	7 0 49149	1 49 91997	-0.0618	0.17474	17.74812	-0.00377	2.5 T	m/						1
sream	4	1 11070	8 0 46027	3 41 4161	2 -0 05297	0.273397	24.6127	-0.00526								1
	3	4 0044	6 0.400Z/	2 38 72724	0.06463	0 387508	31,47532	-0.00865	- 4 †	•	-	8-8-1	1-8-8	S.	t.	
	4	1,2311	J U.4/0/3	a 37 071	2 _0 07150	0 395379	30 36219	-0.01628	1.5 +	1	r .	B. B. I	-0-0			
	5	1.30220	0 0.49383	a 31.323		C 1201019	32 1003	-0.01529		N	8-8-			8-8	ha	The !
	6	1.33957	4 0.45489	34,/0498		0 44407	27 52727	-0.01922	11		18-11-	8-8-1	-11-1	h	-	B-R H
	7	1.35576	9 0.47595	35 1060	-0.09906	0 4410/	32.33202	0.01322	0.5 +	1			•		B	La R
	8	1.37302	4 0.49883	39 36:3313	8 -0 1285	0 468518	34.12306	-0.03362			w —		,			THE L
	9	1.37511	8 0.51342	29 37 3370	9 -0.19123	3 0.475335	34.56682	-0.03494	0 1							45 40
	10	1.32422	26 0,50916	3 38.4498	6 -0.1923	5 0 475851	35.93427	-0.0484	-0.5 9	2	4	6	8 1	U 1	2 1	4 10 18
	11	1.23058	35 0.50839	6 41.3133	5 -0.1534	7 0.48343	39.28461	-0.05331					· .			Radial (mm)
	12	1,15167	75 0.49809	35 43 2496	3 -0,1366	8 0 480676	6 41.73715	-0.043	-1 t							
	13	1.0139	41 0.4930	18 48.623	9 -0.0809	6 0.479898	47.33003	-0.03261	-1.5 1	6)						
	14	0 8732	53 0.4789	96 54.8519	3 -0.0449	9 0.453271	51.90606	-0.01273			20	4				
	15	0.7550	36 0 44260	15 58 6203	4 0.0160	8 0.423506	56,09078	-0.00621		_	_					
	10	0.73300	17 0 4405	19 65 6494	1 0.0036	5 0.423998	63,18735	-0.02088								
	47	0.5038	87 0 4205	91 83 4692	2 0.03849	8 0.38664	3 76,73208	-0.01634								
	11	0.3030	01 0.7200	16 117 553	8 0.03462	1 0 34759	4 108 4465	-0.00401								
	18	0.3203	21 0,3700	10 117.904	0 00-02											
	_		I HOUS	11 71 16 31			W TURBU	LIW .								
X	D .	U MEAN	U U RMS	U TURB	U W MEAN	WRMS	W TURBU	UW 0.000025			20 de			tel ve	lacity	
X 3d dow	D 1	U MEA)	U RMS	U TURB 47 27,4554	U W MEAN	W RMS	W TURBU 6 1.845259 8 4.063463	0.000025	25.		3D do	wnstre	am ax	ial ve	lacity	
X 3d dow stream	D 1 2	U MEAN 1.2494 1.3945	U RMS 69 0,3430 69 0,3483	0 TURB 47 27.4554 69 24.5804	U W MEAN 46 -0.0323 42 -0.0705	W RMS 6 0 02305 4 0 05666	W TURBU 6 1.845259 8 4.063463	0.000025 0.000084	2.5	m/s	30 do	winstre	am ax	ial ve	lacity	
X 3d dow stream	D 1 2 3	U MEAN 1.2494 1.3945 1.4930	U RMS 69 0.3430 69 0.3483 36 0.3510	U TURB 47 27,4554 69 24,9804 12 23,5099	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651	W RMS 6 0.02305 4 0.05666 16 0.1675	W TURBU 6 1.845259 8 4.063463 1 11.21945	0.000025 0.000084 -0.00101	2.5 2 -	m/s	3D do	wnstre	am ax	ial ve	locity	
X 3d dow stream	D 2 3 4	U MEA) 1.2494 1.3945 1.4930 1.5343	V URMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456	U TURB 47 27,4554 69 24,9804 112 23,5099 113 22,525	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552	W RMS 6 0.02305 4 0.05666 16 0.1675 29 0.32524	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753	0.000025 0.000084 -0.00101 0.003914	2.5	m/s	30 do	wnstre	eam ax 	ial ve	lacity	**
X 3d dow stream	D 2 3 4 5	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954	N URMS 69 0,3430 69 0,3483 36 0,3510 44 0,3456 83 0,356	U TURB 47 27,455- 69 24,980- 112 23,509 113 22,525 119 22,324	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 92 -0.0446	W RMS 6 0.02305 4 0.05666 16 0.1675 29 0.32524 57 0.30498	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568	0.000025 0.000084 -0.00101 0.003914 0.00459	2.5 2 1,5	m/s	30 do	wnstre	eam ax	ial ve	locity	R. B. B. B.
X 3d dow stream	D 1 2 3 4 5 6	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250	N URMS 69 0.3430 69 0.3483 136 0.3510 144 0.3456 183 0.356 186 0.3572	U TURB 47 27,455- 69 24,920- 12 23,509 13 22,525 519 22,324 262 21,984	U W MEAN 46 -0.0323 42 -0.0705 55 -0.0651 11 -0.0552 52 -0.0446 22 -0.0430	W RMS 6 0 02305 4 0 05666 16 0 1675 29 0 32524 57 0 30498 39 0 31425	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777	0.000025 0.000084 -C.00101 0.003914 0.00459 0.007302	2.5 2 1,5 1	m/s	30 do	wnstre 	am ax 	ial ve	locity	
X 3d dow stream	D 1 2 3 4 5 6 7	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475	N U RMS 69 0.3430 69 0.3483 136 0.3510 144 0.3456 183 0.356 186 0.3572 529 0.3620	U TURB 47 27.455- 69 24.920- 12 23.509 13 22.525 19 22.324 262 21.984 267 21.975	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 52 -0.0446 22 -0.0430 35 -0.025	W RMS 6 0 02305 4 0 05666 16 0 1675 29 0 32524 57 0 30498 59 0 31425 57 0.32725	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306	2.5 2 1.5 1	m/s	30 do	wnstre - B-B - D-D - B-B	am ax -9-9- -9-9-	ial ve 5-9 6-9	locity	R R R R R R R R R R R R R R R R R R R
X 3d dow stream	D 1 2 3 4 5 6 7 8	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 83 0.356 986 0.3572 529 0.3620 733 0.3629	U TURB 47 27,455- 69 24,980- 112 23,509 113 22,525 119 22,324 262 21,984 267 21,975 266 22,336	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 92 -0.0446 22 -0.0436 35 -0.025 37 -0.025	W RMS 6 0.02305 4 0.05666 16 0.1675 29 0.32524 57 0.30498 59 0.31425 57 0.32725 54 0.33527	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63579	0.000025 0.000025 0.000084 0.003914 0.00459 0.007302 0.007306 0.006759	2.5 2 1.5 1	m/s	30 do	wnstre -12-13 -12-13 -12-13 -12-13	am ax -9-9- -9-8-	ial ve	lacity	
X 3d dow stream	D 1 2 3 4 5 6 7 8 9	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.6247	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 183 0.356 186 0.3572 529 0.3620 733 0.3629 379 0.3691	U TURB 47 27,4554 69 24,9804 112 23,5059 113 22,525 119 22,3249 125 21,9849 1267 21,975 1366 22,336 165 22,839	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0654 11 -0.0552 92 -0.0446 22 -0.0436 35 -0.025 37 -0.025 92 -0.0133	W RMS 6 0.02305 6 0.05666 16 0.1675 29 0.32524 67 0.30498 09 0.31425 97 0.32725 94 0.33527 35 0.33834	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215	0.000025 0.000025 0.000084 0.000914 0.003914 0.00459 0.00459 0.007306 0.007306 0.006759 0.012111	2.5 2 1.5 1 0.5	m/s	30 do	wnstre 	eam ax -9-9- -9-9- -9-9- -9-9-	ial ve B-g D-g B-g	lacity	
X 3d dow stream	D 1 2 3 4 5 6 7 8 9	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.6163 1.5750	N U RMS 69 0.3430 69 0.3483 136 0.3510 144 0.3456 183 0.3572 529 0.3620 733 0.3629 737 0.3637 147 0.3740	U TURB 47 27.4554 69 24.5604 112 23.5056 113 22.525 119 22.324 1262 21.584 1262 21.975 1266 22.336 125 22.839 1265 22.839 1266 23.745	U W MEAN 46 -0.0323 42 -0.0705 59 -0.065 92 -0.0446 22 -0.0446 22 -0.0436 35 -0.025 37 -0.025 37 -0.013 87 -0.013	W RMS 6 0.02305 54 0.05666 15 0.1675 29 0.32524 67 0.30498 0.30498 0.30498 0.31425 97 0.32725 54 0.33527 35 0.33834 85 0.33854	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63578 3 20.93215 3 20.93215	UW 0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007305 0.006759 0.006759 0.0121111 0.012747	2.5 2 1.5 1 0.5 0	m/s	30 do		eam ax	ial ve	locity	14 16 18
X 3d dow stream	D 1 2 3 4 5 6 7 8 9 10	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.6163 1.5750 1.517	N U RMS 69 0.3430 69 0.3483 136 0.3510 144 0.3456 183 0.3572 529 0.3620 733 0.3629 379 0.3691 144 0.3728	U TURB 47 27.455- 69 24.980- 112 23.509 113 22.525 119 22.324 1262 21.984 1262 21.984 1266 22.336 1265 22.839 129 23.745 120 24.572	U W MEAN 46 -0.0323 42 -0.0705 59 -0.065 92 -0.0436 22 -0.0436 35 -0.025 37 -0.025 37 -0.013 87 -0.013 74 -0.046	W RMS 6 0.02305 54 0.05666 16 0.1675 129 0.32524 167 0.30498 199 0.31425 197 0.32725 194 0.33527 195 0.33834 195 0.33834 195 0.33854 196 0.33537 196 0.33557 196 0.35577 196 0.355777 196 0.355777 196 0.355777 196 0.355777 196 0.355777 196 0.355777 196 0.3557777 196 0.3557777 196 0.35577777777777777777777777777777777777	W TURBU 6 1.845259 8 4.063463 1 11.219453 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 2 22.13855	UW 0.000025 0.010084 -0.0101 0.003914 0.00459 0.00459 0.007302 0.0007305 0.0007306 0.0012111 0.012747 0.006358	2.5 2 1.5 1 0.5 0 -0.5	m/s	30 do	winstre	am ax 	ial ve	locity	14 16 18 Radiat (mm)
X 3d dow stream	D 1 2 3 4 5 6 7 8 9 10 11	U MEAA 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.6163 1.5750 1.517 ⁻¹ 1.4120	N U RMS 69 0.3430 69 0.3430 36 0.3510 444 0.3456 986 0.3572 529 0.3620 733 0.3625 733 0.3625 739 0.3691 047 0.3785	U TURB 47 27.4554 69 24.9804 112 23.5091 113 22.525 319 22.3241 262 21.9841 267 21.976 306 22.336 165 22.839 209 23.745 304 24.572 315 26 776	U W MEAN 46 -0.0232 42 -0.0705 55 -0.0655 52 -0.0446 22 -0.0436 35 -0.025 37 -0.025 37 -0.025 37 -0.025 37 -0.013 37 -0.013 37 -0.013 51 -0.0426 51 -0.032	W RMS 86 0.02305 84 0.05666 85 0.1675 89 0.32524 87 0.30498 89 0.31425 97 0.32725 84 0.33527 85 0.3383 85 0.3383 86 0.33587 15 0.32281 15 0.32581 15 0.32581 15 0.32581 15 0.32581 15 0.32581 15	W TURBU 6 1.845259 8 4.063463 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 4 22.13856 2 22.8509	UW 0.000025 0.010084 -0.00101 0.00314 0.00459 0.00459 0.00459 0.00459 0.00459 0.00459 0.00459 0.00459 0.00459 0.00459 0.006759 0.012111 0.012747 5 0.006358 3 0.00453	2.5 2 - 1.5 - 1 - 0.5 -0.5 -1	m/s	30 do	winstre 	am ax 	ial ve	locity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 5 6 7 8 9 10 11 12	U MEA/ 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.6163 1.5750 1.5750 1.517500 1.517500 1.517500 1.517500 1.5175000 1.5175000 1.51750000000000000000000000000000000000	N U RMS 69 0.3430 69 0.3430 36 0.3510 444 0.3456 883 0.3562 733 0.3629 733 0.3629 733 0.3629 739 0.3631 747 0.3740 144 0.3725	U TURB 47 27.4554 69 24.920- 112 23.5091 13 22.525 119 22.3241 22.3242 22.1.584 22.336 165 22.839 209 23.745 209 23.745 204 24.572 315 25.776 373 28.054	U W MEAN 45 -0.0232 42 -0.0705 55 -0.0655 52 -0.0446 22 -0.0436 35 -0.025 37 -0.025 37 -0.025 37 -0.025 37 -0.013 37 -0.013 37 -0.045 51 -0.032 55 -0.031	W RMS 86 0.02305 84 0.05666 85 0.1675 92 0.32524 87 0.30498 90 0.31425 97 0.32725 94 0.33527 15 0.3384 85 0.3384 86 0.33587 15 0.3228 91 0.3248 91 0.32	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11558 5 19.33777 1 19.86316 6 20.63575 13 20.93215 12 21.51811 14 22.13855 2 22.85095 2 24.41865	UW 0.000025 0.000025 0.000024 -0.00101 0.003914 0.00459 0.00459 0.007302 0.002759 0.00121111 0.012747 0.006358 0.006358 0.006358 0.006353 0.006453	2.5 2 - 1.5 - 1 - 0.5 -0.5 -1	m/s	30 do	wnstre	am ax 9-9- 9-9- 9-9- 1- 8	ial ve	lacity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 5 6 7 8 9 10 11 12 13	U MEA/ 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.6163 1.5750 1.517 2.1.4128 3.1.3283 1.3283 1.2433	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 88 0.3572 529 0.3620 733 0.3625 733 0.3625 734 0.3745 744 0.3725 745 0.3745 745 0.3745 745 0.3745 745 0.3745 745 0.3745 745 0.3765 745 0.3765 74	U TURB 47 27.4554 69 24.9804 112 23.509 113 22.525 119 22.324 119 22.324 119 22.324 119 22.324 119 22.336 106 22.336 106 22.336 106 22.336 106 22.336 106 22.336 106 22.336 106 22.336 106 22.336 107 21.975 107 21.975 21.975 21.975 21.975 21.975 21.975 21.975 21.975 21.975 21.975 21.975 21.975 21.9	U W MEAN 46 -0.0323 42 -0.0705 55 -0.0651 11 -0.0552 52 -0.0446 22 -0.0436 35 -0.026 37 -0.0263 37 -0.0133 37 -0.0133 74 -0.0406 51 -0.032 157 -0.031 157 -0.031 157 -0.031 157 -0.031 154 -0.021 154 -0.021 155 -0.021	W RMS 16 0.02305 26 0.02305 26 0.05666 15 0.1675 29 0.32524 57 0.30498 29 0.31425 29 0.31425 29 0.33527 35 0.33834 25 0.33834 25 0.33836 26 0.33527 315 0.3283 201 0.3248 201 0.3248 201 0.3249	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 4 22.13855 2 24.8185 2 24.8186 3 24.9016	UW 0.000025 0.000084 -0.0011 0.003914 0.00459 0.007302 0.007302 0.002759 0.007302 0.007305 0.002759 0.006759 0.006759 0.006753 0.006358 0.009453 0.009453 0.009453 0.004007	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	30 do	wnstre	am ax 9-9- 9-9- 9-9- 1- 8	ial ve	lacity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 5 6 6 7 8 9 10 11 12 13 14	U MEAX 1.2494 1.3945 1.4930 1.5343 1.5554 1.6250 1.6475 1.6247 1.6163 1.5750 1.5177 2.1.4128 3.1.3283 4.1.2243 5.1.225 1.2243 5.1.225 1.2243 5.1.225 1.2243 5.1.225 1.2243 5.1.225 1.2243 5.555 1.225 1.255 1	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 83 0.3572 329 0.3620 733 0.3629 733 0.3629 733 0.3629 737 0.3740 144 0.3726 361 0.3765 987 0.3731 705 0.3501 705 0.3501 70	U TURB 47 27,4554 69 24,9504 12 23,509 13 22,525 19 22,324 62 21,984 66 22,336 655 22,839 009 23,745 304 24,572 315 26,776 373 28,094 955 28,218 762 29,94	U W MEAN 45 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 52 -0.0446 22 -0.0436 37 -0.0253 67 -0.0133 77 -0.0133 74 -0.0466 151 -0.032 157 -0.031 154 -0.021 155 -0.0	W RMS 16 0.02305 16 0.02305 16 0.05666 16 0.1675 19 0.32524 19 0.32524 19 0.32525 19 0.32525 19 0.32525 19 0.3383 15 0.3258 15 0.3588 15 0.35888 15 0.35888 15 0.35888 15 0	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 2 21.51811 2 22.8509 3 24.41865 3 24.41865 2 25.4005	UW 0.000025 0.010084 -0.010084 -0.0111 0.003914 0.007302 0.007302 0.007302 0.000759 0.002759 0.002759 0.002759 0.002759 0.002759 0.002759 0.002759 0.002759 0.002757 0.002757 0.002558 0.004007 0.005808 0.005808 0.003384	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	wnstre	eam ax 9 9 9 9 9 9 1 8	ial ve	locity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 4 5 6 6 7 7 8 9 10 11 11 12 13 14	U MEAX 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.61650 1.5177 1.61650 1.5177 1.4126 3.1.2283 4.1.2435 1.1255	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 883 0.3572 329 0.3622 379 0.3622 379 0.3623 379 0.3623 379 0.3623 379 0.3623 379 0.3623 379 0.3623 379 0.3623 370 0.3742 144 0.3723 384 0.3733 705 0.3503 674 0.320	U TURB 47 27.4554 47 27.4554 69 24.9204 112 23.5093 113 22.525 119 22.3243 1262 21.9843 1262 21.9863 1262 21.9863 1265 22.336 1265 22.839 1209 23.745 304 24.572 315 26.776 315 28.094 955 28.218 762 29.36 2762 29.34	U W MEAN 46 -0.0323 42 -0.0705 59 -0.065 59 -0.0436 22 -0.0436 22 -0.0436 35 -0.025 37 -0.025 37 -0.025 37 -0.032 37 -0.0426 51 -0.032 157 -0.031 154 -0.021 135 -0.0121 135 -0.0121 13	W RMS 16 0.02305 26 0.02305 26 0.02566 36 0.1675 29 0.32524 37 0.30498 29 0.31425 57 0.32725 54 0.33834 25 0.33834 26 0.33834 27 0.32284 26 0.33834 27 0.32284 26 0.33837 27 0.32284 28 0.30971 39 0.28599 328 0.28590	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 2 21.51811 2 22.8509 5 24.4186 3 24.9016 2 24.4186 3 24.9016 2 5 4.005 5 28.4075	UW 0.000025 0.000025 0.000026 0.000026 0.000026 0.000026 0.000026 0.000026 0.000026 0.0003914 0.00459 0.0007302 0.0007306 0.0012111 0.012747 5.0006358 3.0004007 8.000384 2.000384 2.000384	2.5 2 - 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	wnstre	eam ax 	ial ve	lacity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 5 6 6 7 7 8 9 9 10 11 12 13 14 13	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.61635 1.5750 1.5175 1.61635 1.5750 1.5175 1.1255 1.1255 1.0297 2.0297	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 83 0.3572 329 0.3621 330 0.3623 379 0.3691 047 0.3744 144 0.3728 361 0.3783 367 0.3733 705 0.350 674 0.330 047 0.323	U TURB 47 27.4554 47 27.4554 69 24.9204 112 23.5091 113 22.525 119 22.3241 1262 21.984 1262 21.986 1262 21.986 1265 22.839 1209 23.745 304 24.572 315 26.766 373 28.094 955 28.212 762 29.32 426 31.422	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 59 -0.0446 22 -0.0436 35 -0.025 37 -0.0253 37 -0.0253 37 -0.0131 367 -0.031 354 -0.021 354 -0.021 355 -0.011 354 -0.021 355 -0.011 354 -0.021 354 -0.021 355 -0.011 354 -0.021 355 -0.011 354 -0.021 355 -0.011 355 -0.021 355 -0.025 357 -0.055 357 -0.05	W RMS 16 0.02305 26 0.02305 26 0.02566 27 0.32524 28 0.31425 29 0.31425 24 0.33527 25 0.33527 25 0.33527 25 0.33527 25 0.33527 25 0.33527 25 0.33527 25 0.3363 26 0.33527 215 0.3228! 22 0.3228! 23 0.324! 24 0.324! 26 0.326! 21 0.2459' 23 0.2859' 24 0.2872'	W TURBU 6 1.845259 6 4.063463 1 11.21945 3 21.19753 8 19.11558 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 2 21.3856 2 22.45095 3 24.9016 2 24.9016 2 25.4005 3 24.9016 2 8.0876 4 32.327	UW 0.000025 0.000025 0.000026 0.000026 0.000026 0.000026 0.000026 0.000026 0.000026 0.0003914 0.00459 0.007306 0.002759 5 0.00121111 0.012747 5 0.006358 0.0006358 0.0005808 0.0049433 0.0049433 0.0049433 0.0049433 </td <td>2.5 2 - 1.5 - 1 - 0.5 -0.5 -1 -1.5</td> <td>m/s</td> <td>3D do</td> <td>wnstre </td> <td>eam ax</td> <td>ial ve</td> <td>lacity</td> <td>14 16 18 Radial (mm)</td>	2.5 2 - 1.5 - 1 - 0.5 -0.5 -1 -1.5	m/s	3D do	wnstre 	eam ax	ial ve	lacity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 4 5 6 6 7 7 8 8 9 10 11 12 13 14 15 14 15 14	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5554 1.6250 1.6475 1.6275 1.6277 1.6163 1.5750 1.5177 2.1.4126 3.1.3285 1.1255 5.1.1255 5.1.125 5.1.0297 0.892	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 88 0.3572 529 0.3622 529 0.3623 733 0.3623 733 0.3623 747 0.3740 144 0.3725 987 0.3733 987 0.3733 674 0.330 047 0.323 751 0.321 751 0.321 751 0.321 751 0.323 751 0.321 751 0.323 751 0.321 751 0.323 751 0.325 0.325 0.325 0.325 0.325 0.325 0.325 0.325 0.350 0	U TURB 47 27.4554 69 24.920 112 23.509 13 22.525 19 22.324 262 21.984 266 21.975 506 22.336 165 22.839 509 23.745 304 24.572 315 25 776 773 28 094 955 28 218 762 29 38 426 31.425 426 36.000	U W MEAN 46 -0.0323 42 -0.0705 55 -0.065 52 -0.044 22 -0.043 35 -0.025 37 -0.025 37 -0.025 37 -0.013 37 -0.013 37 -0.013 37 -0.032 57 -0.031 35 -0.021 355 -0.021 357 -0.021 357 -0.021 355 -0.021 357 -0.025 357 -0.025 377 -0.0	W RMS 16 0.02305 26 0.02305 24 0.05666 16 0.1675 29 0.32524 57 0.30498 29 0.31425 57 0.32725 54 0.33527 35 0.33834 25 0.33834 25 0.33834 26 0.33527 315 0.32836 26 0.32541 30 0.3244 46 0.30971 39 0.28597 28 0.28798 28 0.28790	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11566 5 19.33777 1 19.86316 6 20.6357 3 20.93215 3 20.93215 3 20.93215 2 21.51811 4 22.1385 2 24.5095 3 24.9016 2 24.5005 3 24.9016 2 25.4005 3 22.2378 2 2.2378 2	UW 0.000025 0.0300084 -0.00101 0.003914 0.007302 0.007306 0.007306 0.006759 0.006759 0.00635 0.006358 0.006358 0.006358 0.006358 0.005808 0.003844 0.004007 0.004943 0.004943 0.007151 0.004943 0.007151 0.007151	2.5 2 1.5 1 .0.5 0 -0.5 -1 -1.5	m/s	3D do	wnstre	eam ax	ial ve	lacity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 4 5 6 6 7 7 8 8 9 10 11 12 13 14 15 14 11 11 11 11	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5954 1.6250 1.6475 1.6247 1.6165 1.5750 1.517 ⁻¹ 1.4126 1.526 1.517 ⁻¹ 1.4126 1.5265 1.2435 5.1.125	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 83 0.352 529 0.3620 733 0.3625 733 0.3625 733 0.3625 747 0.3740 144 0.3726 361 0.3765 987 0.3735 674 0.330 047 0.323 751 0.321 136 0.336	U TURB 47 27.4554 69 24.980 112 23.509 13 22.525 19 22.324 162 21.976 162 21.976 165 22.839 009 23.745 304 24.572 315 26.776 373 28.094 425 28.218 426 31.429 426 31.429 426 36.000 754 46.955 426 36.000	U W MEAN 46 -0.0323 42 -0.0706 55 -0.0651 11 -0.0552 52 -0.044 22 -0.043 35 -0.025 37 -0.0253 37 -0.013 37 -0.013 37 -0.013 57 -0.031 55 -0.021 135 -0.021 135 -0.011 354 -0.021 135 -0.011 354 -0.021 135 -0.011 354 -0.021 135 -0.011 354 -0.021 135 -0.011 354 -0.021 394 0.0107 394 0.0107 304 0.007 304 0.007 305 0.007 305 0.007 305 0.007 305 0.007 300	W RMS 16 0.02305 16 0.02305 16 0.05666 15 0.1675 19 0.32524 17 0.30498 19 0.31425 19 0.31425 19 0.32725 10 0.32725 10 0.32859 15 0.32859 15 0.32959 16 0.2859 18	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 9 21.51811 4 22.13855 2 22.8509 3 24.41865 2 24.41865 2 24.41865 2 25.4005 3 24.9016 2 25.4005 3 28.0876 04 32.2378 2 36.8027 W TURBU	0.000025 0.000025 0.0100084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.000759 0.007302 0.000759 0.002759 0.0012111 0.012747 0.004533 0.009453 0.004588 0.00384 0.004007 0.004007 0.004007 0.004007 0.004888 0.00384 0.00384 0.007384 0.004943 0.007151 0.001675 1.00675	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	30 do	wnstre 	am ax	ial ve	locity	14 16 18 Radial (mm)
X 3d dow stream	D 1 2 3 4 5 6 6 7 7 8 9 9 10 11 12 13 14 11 12 11 12 12 12 12 12 12 12 12 12 12	U MEAN 1.2494 1.3945 1.4930 1.5554 1.5554 1.5554 1.5554 1.5554 1.6247 1.6163 1.5755 1.6247 1.6163 1.5755 1.5755 1.2433 1.3283 4.1255 1.0297 0.8928 0.717 U MEA	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 88 0.3572 229 0.3622 733 0.3629 733 0.3629 747 0.3742 861 0.3762 987 0.3763 987 0.3763 987 0.3763 987 0.3763 987 0.3763 987 0.3763 987 0.3763 987 0.326 987 0.320 751 0.321 136 0.336 NU RMS	U TURB 47 27,4554 69 24,9204 112 23,5095 113 22,525 119 22,3245 129 22,3245 129 22,3245 129 22,3245 129 22,3245 129 22,3245 129 22,336 129 22,356 129 22,3	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0653 11 -0.0555 59 -0.0430 32 -0.0430 35 -0.025 62 -0.0131 87 -0.0420 51 -0.032 157 -0.031 154 -0.0420 157 -0.031 154 -0.0421 155 -0.031 154 -0.0421 154 -0.042	W RMS 16 0.02305 26 0.02305 26 0.02566 27 0.32524 27 0.3428 29 0.31425 29 0.31425 29 0.33834 25 0.33834 25 0.33834 26 0.33834 27 0.32281 01 0.32281 01 0.3244 64 0.30971 39 0.28590 539 0.28789 539 0.2639 N W RMS	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 2 21.51811 2 22.8509 2 24.41863 3 24.9016 2 24.49016 2 24.49016 2 24.49016 2 24.005 5 28.0876 0 4 32.2378 2 36.8027 W TURB	0.000025 0.000025 0.000026 0.000026 0.000026 0.0003914 0.00459 0.00459 0.006759 0.0017302 0.007302 0.006759 0.0012747 0.0012747 0.0012747 0.002808 0.002848 0.00388 0.00388 0.00388 0.00384 0.00505 0.00505 0.0055 0.001675 0	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	30 do	winstree	eam ax	ial ve	locity	14 16 18 Radial (mm)
X 3d dow stream X 6d dow	D 1 2 3 4 5 6 7 7 8 9 9 10 11 12 13 14 11 12 14 11 12 10 14 11 12 10 14 14 14 14 14 14 14 14 14 14 14 14 14	U MEAN 1.2494 1.3945 1.4930 1.5343 1.5554 1.6250 1.6475 1.6247 1.6163 1.5755 1.577 1.5177 1.5177 1.1125 1.3285	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 88 0.3572 329 0.3620 330 0.3623 379 0.3691 047 0.3744 144 0.3726 861 0.3763 987 0.373 705 0.350 674 0.330 047 0.323 751 0.321 136 0.336 N U RMS 779 0.375	U TURB 47 27.458 47 27.458 47 27.458 47 27.458 69 24.920 112 23.509 13 22.525 19 22.324 162 21.976 306 22.336 165 22.839 209 23.745 304 24.572 315 26.766 315 28.094 955 28.218 762 29.32 426 31.422 426 36.000 754 46.956 U TURI 46.51 453 28.242	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 59 -0.0446 22 -0.0436 35 -0.025 37 -0.0253 37 -0.0253 37 -0.031 367 -0.031 354 -0.021 354 -0.021 355 -0.021 355 -0.021 357 -0.032 357 -0.032 357 -0.032 357 -0.032 357 -0.032 354 -0.021 354 -0.021 354 -0.021 354 -0.021 354 -0.021 354 -0.021 354 -0.021 355 -0.022 357 -0.022	W RMS 16 0.02305 26 0.02305 26 0.02566 27 0.32524 28 0.31425 29 0.31425 29 0.31425 24 0.33527 35 0.33834 25 0.33834 25 0.33836 26 0.33831 15 0.32284 201 0.3244 64 0.30974 39 0.2859 288 0.2898 39 0.2639 N W RMS 188 0.10600	W TURBU 6 1.845259 6 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 2 21.3861 2 22.13851 2 24.4186 3 24.9016 2 24.4186 3 24.9016 2 25.4005 35 28.0876 4 32.2378 2 36.8027 W TURB 81 8.06218 4 2.03777 W TURB	UW 0.000025 0.0300084 0.030914 0.00459 0.00459 0.007302 0.007302 0.007305 0.00121111 0.012747 0.000453 0.00455 0.004	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	30 do	wnstrea	am ax	ial veid	lacity	14 16 18 Radial (mm)
X 3d dow stream 6d dow stream	D 1 2 3 4 5 6 7 8 9 10 11 12 14 15 14 15 14 15 10 11 10 11 10 11	U MEAN 1.2494 1.3945 1.4930 1.554 1.5554 1.6250 1.6475 1.5477 1.6475 1.5477 1.5477 1.5477 1.5475 1.5477 1.5475 1.5475 1.5475 1.1255 1.0297 1.0297 1.0292 1.0292 1.0292 1.0292 1.0292 1.0292 1.0292 1.0292 1.0292 1.0315 1.0295 1.0255	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 883 0.3572 529 0.3622 379 0.3691 047 0.3740 144 0.3722 581 0.3740 144 0.3725 587 0.373 674 0.330 047 0.323 751 0.321 136 0.336 NN U RMS 5779 0.375 1953 0.23	U TURB 47 27.4554 47 27.4554 69 24.920 112 23.5091 13 22.525 19 22.3241 262 21.924 262 21.926 165 22.336 209 23.745 204 24.572 315 25.776 304 24.572 315 28.044 955 28.218 762 29.32 426 31.425 426 31.425 426 31.425 426 36.005 754 46.955 651 28.541 2021 15.85	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 59 -0.0242 22 -0.0442 22 -0.0432 35 -0.025 37 -0.0133 37 -0.0133 37 -0.0133 37 -0.013 367 -0.031 354 -0.021 355 -0.011 355 -0.011 355 -0.011 355 -0.021 355 -0.021 354 -0.022 354 -0.021 355 -0.011 355 -0.011 355 -0.011 355 -0.011 355 -0.021 354 -0.021 355 -0.011 355 -0.011 355 -0.011 355 -0.011 355 -0.001 354 -0.021 355 -0.011 355 -0.011 355 -0.011 355 -0.011 355 -0.011 355 -0.011 355 -0.011 355 -0.001 355 -0.001 355 -0.021 355 -0.025 354 -0.022 355 -0.025 357 -0.025	W RMS 16 0.02305 16 0.02305 16 0.05666 16 0.1675 17 0.30498 19 0.31425 19 0.31425 10 0.3527 10 0.33527 10 0.33527 15 0.3363 15 0.32285 10 0.3244 64 0.30971 39 0.2859 10 0.2849 10 0.2849 10 0.2849 10 0.2849 10 0.2859 139 0.2639 N W RMS 188 0.1060 505 0.0119	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11566 5 19.33777 1 19.86316 6 20.6357 3 20.93215 3 20.93215 3 20.93215 2 21.51811 4 22.13855 2 24.8005 3 24.9016 2 25.4005 3 24.9016 2 25.4005 3 24.9016 2 36.8027 W TURB 81 8.06218 48 0.81782 4 0.81782 4 21.2175 4 21.21	Uw 0.000025 0.000024 0.000084 -0.00101 0.003914 0.007302 0.007306 0.0007306 0.0007306 0.0007306 0.0007306 0.0007306 0.000453 0.000453 0.000588 0.0005808 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.0004943 0.000164 0.0001675 Uw 8 -0.00188 9 0.000064	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	30 do	wnstrea	eam ax	ial ve B B B B B B C C C C C C C C	lacity	14 16 18 Radial (mm)
X 3d dow stream 6d dow stream	D 1 2 3 4 5 6 7 8 9 10 11 12 14 15 14 15 14 15 14 15 14 15 14 15 14 15 16 17 17 17 17 17 17 17 17 17 17 17 17 17	U MEAN 1.2494 1.3945 1.4930 1.554 1.5554 1.6250 1.6475 1.1255	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 88 0.3572 529 0.3620 733 0.3629 733 0.3629 747 0.3740 144 0.3725 987 0.3735 987 0.3735 0.374 0.3735 0.374 0.3735 0.321 136 0.336 NU U RMS 7779 0.375 953 0.221 7798 0.221	U TURB 47 27.4554 47 27.4554 69 24.920 112 23.509 13 22.525 19 22.324 162 21.976 165 22.336 165 22.336 165 22.336 165 22.336 165 22.337 209 23.745 304 24.572 315 26.766 373 28.094 426 31.429 426 31.429 426 31.429 426 31.429 426 31.429 426 31.429 426 31.429 425 36.000 7754 46.9561 46.51 28.544 4021 15.81 1729 14.72	U W MEAN 46 -0.0323 42 -0.0705 55 -0.065 52 -0.044 22 -0.043 53 -0.025 53 -0.025 53 -0.025 53 -0.025 53 -0.013 57 -0.013 57 -0.013 55 -0.021 55 -0.021 55 -0.025 BU W MEA 569 -0.065 944 -0.025 965 -0.025 565 -0.025	W RMS 60 0.02305 64 0.05666 65 0.1675 29 0.32524 57 0.30498 29 0.31425 57 0.32725 57 0.33834 25 0.33834 25 0.33834 25 0.33834 25 0.33834 25 0.33834 25 0.33834 25 0.33834 26 0.33527 315 0.32285 01 0.3244 26 0.3097 39 0.2859 28 0.2878 539 0.2639 9 0.26	W TURBU 6 1.845259 6 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63578 3 20.93215 2 21.51811 4 22.13855 2 24.41865 2 24.41865 2 24.41865 3 24.9016 2 25.40055 3 24.9016 2 36.8027 W TURB 81 8.06218 48 0.81782 84 0.84231	Uw 0.000025 0.000024 0.000084 -0.00101 0.003914 0.007302 0.007302 0.000759 0.007302 0.007302 0.007303 0.006759 0.006759 0.006358 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000407 8 0.00384 2 0.004943 8 0.001675 Uw -0.00188 29 0.0006443 -4.8E-05	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2	2	30 do	wnstree	am axi	ial ve	12	14 16 18 Radial (mm)
X 3d dow stream 6d dow stream	D 1 2 3 4 5 6 6 7 8 9 10 11 12 13 14 11 11 11 11 11 11	U MEAN 1.2494 1.3945 1.4930 1.5554 1.5554 1.5554 1.5575 1.6247 1.6163 1.5775 1.5177 2.1.4125 1.223 1.3283 4.1.253 2.1.4125 2.1.41029 7.0.892 8.0,717 U MEA 1.3152 2.1.4603 3.1.5554 1.5544 1.	N U RMS 69 0.3430 69 0.3483 36 0.3510 44 0.3456 883 0.3562 379 0.3629 379 0.3629 379 0.3629 379 0.3629 379 0.3629 379 0.3629 379 0.3629 379 0.3629 379 0.3740 387 0.3740 387 0.3740 387 0.3740 387 0.3740 387 0.3751 3987 0.321 136 0.336 NU RMS 5779 0.375 3953 0.221 1886 0.2217	U TURB 47 27.4554 47 27.4554 47 27.4554 69 24.9204 112 23.5093 113 22.525 119 22.3243 122 21.9863 1262 21.9864 1262 21.9863 1203 23.7455 1204 24.572 215 25.776 215 25.776 215 26.776 215 28.094 955 28.218 762 29.36 426 36.000 7754 46.953 426 36.000 7754 46.953 2021 15.84 7799 14.72' 7279 13.97	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0653 51 -0.0555 52 -0.0430 32 -0.0255 52 -0.0430 337 -0.0255 52 -0.0133 537 -0.032 537 -0.032 557 -0.031 154 -0.0420 551 -0.032 155 -0.032 155 -0.032 155 -0.032 155 -0.021 1355 -0.025 1355 -0.025	W RMS 16 0.02305 16 0.02305 16 0.02305 16 0.02305 16 0.02305 16 0.30566 16 0.31425 17 0.30498 19 0.31425 10 0.3272 10 0.3283 115 0.32281 11 0.32281 11 0.32281 11 0.3244 15 0.32890 15 0.28590 15 0.28590 1638 0.28590 1638 0.10600 1638 0.10600 1638 0.10600 16357 0.0126 1635 0.0126 1639 0.2639	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 2 21.51811 2 21.51811 2 21.51811 2 22.8509 5 24.4186 3 24.9016 2 22.8509 5 24.4186 3 24.9016 2 22.8509 5 24.4186 3 24.9016 2 22.8509 5 24.4186 3 24.9016 4 22.2378 2 36.8027 W TURB 8 1 8.06218 8 8 0.81782 84 0.84231 61 1.54100	UW 0.000025 0.000025 0.000026 0.000026 0.000026 0.000026 0.000026 0.000026 0.000026 0.00459 0.007302 0.0017305 0.0012747 0.0012747 0.0012747 0.00453 0.00453 0.00453 0.00453 0.00453 0.00453 0.00443 0.00188 0.000645 0.000645 0.00188 0.00188 0.000188 0.000184 0.000184 0.000183 4.8E-05 4.000183	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	30 do	Kinstrea	e me e e e e e e e e e e e e e e e e e e	ial ve	lacity	14 16 18 Radial (mm)
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X 3d dow stream 6d dow stream	D 1 2 3 3 4 4 5 6 6 7 7 8 9 10 11 12 13 14 11 12 13 14 11 12 14 11 12 14 14 15 14 14 15 14 14 15 16 16 17 17 18 17 10 10 10 10 10 10 10 10 10 10 10 10 10	U MEAN 1.2494 1.3945 1.4930 1.554 1.5554 1.6250 1.6475 1.6250 1.6475 1.6250 1.6475 1.6250 1.6475 1.6250 1.6275 1.6275 2.1.4125 3.1326 3.1326 3.1326 3.1326 3.1326 3.1326 3.1325 5.1.577 U MEA 1.5155 5.1.577 6.1.554 5.1.577 6.1.554 5.1.577 6.1.554 7.1.555 8.1.600 9.1.556 1.560 1.560 1.560 1.556 1.556 1.556 1.556 1.555 1.55	N U RMS 69 0.3430 69 0.3451 69 0.3451 69 0.3451 69 0.3452 69 0.3510 644 0.3455 690 0.3572 629 0.3625 629 0.3625 629 0.3625 629 0.3625 629 0.3625 629 0.3625 629 0.3625 629 0.3625 629 0.3625 627 0.3735 627 0.3735 627 0.375 627 0.375 628 0.215 6368 0.217 6368 0.217 6368 0.211 6368 0.211 6378 0.221 6378 0.221 6386 0.211 6386 0.	U TURB 47 27.4584 47 27.4584 469 24.982 112 23.5091 13 22.525 19 22.3241 262 21.984 262 21.984 262 21.984 262 21.984 265 22.336 209 23.745 304 24.572 315 26.761 373 28.954 955 28.218 762 29.32 426 31.425 4265 36.001 754 46.955 2279 13.97 3265 13.51 7328 13.71 4699 13.54 3912 13.98 5288 13.59 60542 13.91 1563 14.55 60242 13.91 1563 14.55 613.74 14.55	U W MEAN 46 -0.0323 42 -0.0705 55 -0.0651 11 -0.0552 52 -0.0442 22 -0.0432 35 -0.025 37 -0.0133 37 -0.0133 37 -0.0133 37 -0.0133 37 -0.0133 37 -0.0133 37 -0.0133 37 -0.0133 37 -0.021 35 -0.021 355 -0.022 394 -0.021 395 -0.025 392 -0.036 594 -0.025 944 -0.025 944 -0.025 945 -0.022 945 -0.025 945 -0.022 945 -0.025 945 -0.025	W RMS 16 0.02305 16 0.02305 16 0.02305 16 0.1675 29 0.32524 57 0.3248 29 0.31425 57 0.32725 4 0.33527 35 0.33834 25 0.33834 25 0.33834 25 0.3383 26 0.3248 27 0.3248 28 0.2859 29 0.2859 239 0.2859 239 0.2639 39 0.2639 39 0.2639 30 0.2639 3188 0.1060 557 0.0126 201 0.1628 201 0.1628 201 0.1628 201 0.1624 201 0.1644 642 0.172* 552 0.17 552	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11556 5 19.33777 1 19.86316 6 20.6357 3 20.93215 3 20	UW 0.000025 0.000024 0.000024 0.000024 0.000024 0.000024 0.000024 0.000024 0.0003914 0.00459 0.007302 0.007306 0.002759 0.00121111 0.0121717 0.006358 0.000453 0.000588 0.004943 0.004943 0.000588 0.000443 0.000183 0.000064 13 4.8E-005 0.000183 0.000645 0.000645 0.000645 0.000645 0.000645 0.000645 0.000657 0.000645 0.000657 0.000657 0.000647 0.000735 0.000507 0.000507 0.000507 0.000507 0.000507 0.00050	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 5 1 5 1 5 1 5 1 5 1 5 1 5 1 5 1 5	m/s	30 do	wnstred	am axi 	ial ve i i i i i i i i i i i i i	locity 12	14 16 18 Radial (mm)
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X 3d dow stream \$tream	D 1 2 3 3 4 5 5 6 7 7 8 9 10 111 12 13 14 13 14 13 14 13 14 13 14 13 14 13 14 13 14 13 14 13 14 15 10 1 1 1 1 2 3 4 5 5 6 7 7 8 9 10 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	U MEAN 1.2494 1.3945 1.4930 1.554 1.5554 1.5554 1.5554 1.5575 1.6247 1.6163 1.5775 1.5177 2.1.4125 3.1.3029 8.0,717 U MEA 1.1.255 1.0297 7.0.892 8.0,717 U MEA 1.1.315 2.1.460 3.1.5554 5.1.577 6.1.555 8.1.601 1.557 6.1.555 8.1.601 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 6.1.555 1.557 1.555 1.517 1.3 1.48 1.4 1.4 1.4 1.3 1.555 1.577 1.3 1.4 1.4 1.4 1.4 1.3 1.557 1.39 1.555 1.577 1.555 1.577 1.39 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.555 1.577 1.39 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.555 1.555 1.577 1.39 1.555 1.5	U RMS 69 0.3430 69 0.3463 69 0.3451 136 0.3510 144 0.3453 183 0.3562 186 0.3572 137 0.3622 133 0.3622 1347 0.3742 144 0.3742 144 0.3762 1361 0.3763 144 0.3763 150 0.3621 161 0.3763 1705 0.3502 674 0.3300 047 0.3213 1360 0.2213 1366 0.2113 1366 0.2113 1495 0.2113 1495 0.2113 15366 0.2113 16366 0.2113 17906 0.2113 18536 0.2214 14451 0.2113 14591 0.2113 1034 0.2113	U TURB 47 27.453- 47 27.453- 47 27.453- 47 27.453- 69 24.920- 112 23.509- 113 22.525- 119 22.324- 122 21.984- 122 21.984- 125 22.336- 1262 21.984- 125 22.839- 120 23.745- 315 25.776 315 25.776 315 25.776 315 25.776 315 25.776 31426 36.000 7754 46.956 31 275 3265 13.51 7338 13.71 3265 13.51 7391 14.72 7279 13.97 33912 13.94 5288 13.59 6042 14.51 314.95 23224 <	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0653 11 -0.0552 59 -0.0446 22 -0.0436 35 -0.025 37 -0.0253 37 -0.0253 37 -0.032 37 -0.032 394 0.006 394 0.006 394 0.006 394 -0.025 394 0.006 394 -0.025 392 -0.036 677 -0.04 395 -0.025 392 -0.036 677 -0.04 195 -0.025 394 -0.05 394 -0.05 395 -0.05	W RMS 16 0.02305 16 0.02305 16 0.02305 16 0.02305 16 0.02566 16 0.30527 17 0.30498 19 0.31425 19 0.31425 10 0.3272 10 0.3243 15 0.32284 15 0.32284 10 0.3244 64 0.30974 39 0.2859 164 0.30272 17 0.2859 188 0.1060 154 0.2878 1539 0.2859 154 0.1010 1557 0.1026 1557 0.1026 1550 0.1029 1550 0.1029 154 0.1642 648 0.172 1552 0.167 154 0.1642 6520 0.1642	W TURBU 6 1.845259 6 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 22 22.8509 32 24.9016 22 22.8509 32 24.9016 28 24.41863 33 24.9016 28 25.4005 35 28.0876 W TURB 8.06278 48 0.81782 48 0.81782 491 10.2746 91 10.2746 92 10.5200 504 10.5756 203 10.4755 303 11.289 219 11.388 879 11.80 6003 12.220	Uw 0.000025 0.000025 0.000024 0.000024 0.000024 0.000024 0.000024 0.000024 0.0003914 0.00459 0.007302 0.0017306 0.00121111 0.012747 5.00121111 0.002453 0.0049433 0.0049433 0.0049433 0.0004943 8.0007151 5.0010675 Uw 8.0007151 9.000064 9.000064 63.000064 63.000675 9.000064 63.000675 9.000064 63.000677 10.000577 64.0007900 67.000470 69.0006207 41.000537 15.000630 119.000319 10.00319 119.000433	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 4 7 0.5 1 5 1 5 1 5 1 5 1 5 1 5 1 5 1 5 1 5 1	m/s	30 do	wnstrea 	am axi B B B B B B B B B B B B B B B B B B B	ial ve 	locity 1 12	14 16 18 Radial (mm)
X 3d dow stream 6d dow stream	D 1 2 3 4 5 6 6 7 7 8 9 10 11 11 12 10 14 11 12 10 11 12	U MEAN 1.2494 1.3945 1.4930 1.554 1.5554 1.6250 1.6475 1.6250 1.6475 1.6250 1.6275 1.6277 1.6163 1.5755 1.5775 1.1255 1.0297 0.8928 0.717 U MEA 1.3155 1.557 5.1.577 0.8928 8.0.717 U MEA 1.3155 1.555 1.577 0.8928 8.0.717 U MEA 1.3155 1.555 1.577 0.8928 8.0.717 U MEA 1.3155 1.555 1.577 0.8928 8.0.717 U MEA 1.3155 1.555 1.577 0.8928 8.0.717 U MEA 1.3155 1.555 1.577 0.8928 8.0.717 1.555 1.557 1.555 1.577 0.8928 8.0.717 1.555 1.577 0.8928 8.0.717 1.555 1.577 0.1555 1.557 1.555 1.577 0.8928 8.0.717 1.555 1.557 1.555 1.577 0.8928 8.0.717 1.555 1.557 1.555 1.577 0.8928 8.0.717 1.555 1.557 1.555 1.577 0.8928 8.0.717 1.555 1.557 1.555 1.577 0.8928 8.0.717 1.555 1.557 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.577 1.555 1.125 1.557 1.555 1.577 1.555 1.555 1.577 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.555 1.55 1.555	N U RMS 69 0.3430 69 0.3451 69 0.3452 683 0.3510 144 0.3456 183 0.3562 239 0.3622 233 0.3622 233 0.3623 379 0.3624 387 0.3744 144 0.3724 261 0.3763 3647 0.3737 705 0.3502 674 0.3300 047 0.3237 705 0.3237 705 0.3237 7136 0.3237 7079 0.375 9953 0.221 3026 0.217 3036 0.214 1495 0.221 3086 0.214 1495 0.211 8366 0.214 8366 0.214 8366 0.214 8366 0.21	U TURB 47 27.4584 47 27.4584 47 27.4584 469 24.9204 112 23.5093 113 22.525 119 22.3243 1262 21.9765 1262 21.9765 1262 21.9843 1265 22.336 1265 22.336 1265 22.337 1262 21.9763 127 23.745 304 24.572 315 26.776 315 26.776 315 28.942 762 29.32 426 36.002 754 46.955 31 2779 13779 14.722 7279 13.971 3012 13.98 5288 13.59 60342 14.59 6342 14.59 6322 14.59 6322 14.53	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 59 -0.0446 22 -0.0436 35 -0.025 37 -0.025 37 -0.025 37 -0.031 37 -0.031 387 -0.031 387 -0.031 387 -0.031 387 -0.031 387 -0.031 387 -0.031 387 -0.032 394 0.0107 394 0.0107 394 0.0107 394 0.0107 394 0.0107 394 0.0107 394 0.0067 394 0.0067 394 0.0067 394 0.007 394 0.007 3	W RMS 16 0.02305 16 0.02305 16 0.02305 16 0.02305 16 0.02566 16 0.1675 17 0.30498 19 0.31425 10 0.32725 14 0.33527 15 0.3248 15 0.3248 15 0.3248 15 0.3248 15 0.3248 164 0.3097 39 0.2859 163 0.2859 173 0.2639 N W RMS 188 0.1060 505 0.0126 505 0.0126 505 0.0126 505 0.0126 505 0.0126 505 0.0126 505 0.0126 505 0.0126 505 0.1126 648 0.1727 552 <td>W TURBU 6 1.845259 6 4.063463 1 11.21945 3 21.19753 8 19.11558 5 19.33777 11 19.6316 6 20.63575 13 20.93215 12 21.51811 14 22.13863 152 22.4406 152 24.41863 152 24.41863 153 24.90164 152 24.41863 153 24.90164 152 24.41863 153 28.0876 154 8.06218 418 8.06218 418 8.06218 418 8.06218 418 8.06218 419 10.2734 191 11.2734 192 10.5203 104 11.263 11.921 11.396 219 10.4755 11.301 11.203</td> <td>Uw 0.000025 0.000025 0.000024 0.000024 0.000024 0.000024 0.000024 0.003914 0.00459 0.007302 0.0007306 0.0017306 0.0007306 0.0007306 0.0006358 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000434 0.000435 0.000435 0.000446 0.000433 0.000433 0.000537 15 0.000433 0.00036 0.00339 0</td> <td>2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 2 1.5 1 0.5 2 -1 -1.5 1 0.5 2 5 1.5 2 1.5 2 -1 -1.5 2 -1 -1.5 -1.5</td> <td>m/s</td> <td>30 do</td> <td>wnstrea b b b b b b c b b b b c b b b b b c b b b b b b b b b b b b b b b b b b b</td> <td>am axi a an axi</td> <td>al velo</td> <td>locity 12</td> <td>14 16 18 Radial (mm)</td>	W TURBU 6 1.845259 6 4.063463 1 11.21945 3 21.19753 8 19.11558 5 19.33777 11 19.6316 6 20.63575 13 20.93215 12 21.51811 14 22.13863 152 22.4406 152 24.41863 152 24.41863 153 24.90164 152 24.41863 153 24.90164 152 24.41863 153 28.0876 154 8.06218 418 8.06218 418 8.06218 418 8.06218 418 8.06218 419 10.2734 191 11.2734 192 10.5203 104 11.263 11.921 11.396 219 10.4755 11.301 11.203	Uw 0.000025 0.000025 0.000024 0.000024 0.000024 0.000024 0.000024 0.003914 0.00459 0.007302 0.0007306 0.0017306 0.0007306 0.0007306 0.0006358 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000453 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000433 0.000434 0.000435 0.000435 0.000446 0.000433 0.000433 0.000537 15 0.000433 0.00036 0.00339 0	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 2 1.5 1 0.5 2 -1 -1.5 1 0.5 2 5 1.5 2 1.5 2 -1 -1.5 2 -1 -1.5 -1.5	m/s	30 do	wnstrea b b b b b b c b b b b c b b b b b c b b b b b b b b b b b b b b b b b b b	am axi a an axi	al velo	locity 12	14 16 18 Radial (mm)
X 3d dow stream 6d dow stream	D 1 2 3 3 4 5 6 6 7 7 8 9 9 100 11 12 13 14 13 14 13 14 13 14 15 10 1 1 2 0	U MEAN 1.2494 1.3945 1.4930 1.554 1.5554 1.6250 1.6475 1.6250 1.6475 1.6250 1.6475 1.6250 1.6275 1.6247 1.6250 1.6257 2.1.4126 3.1326 3.1326 3.1326 3.1326 3.1326 3.1326 3.1326 3.1326 3.1326 3.1326 3.1326 3.1325 5.1.577 6.1.554 3.1.554 3.1.554 5.1.577 6.1.554 3.1.554 3.1.555 1.557 1.555 1.55	N U RMS 69 0.3430 69 0.3451 69 0.3451 69 0.3451 69 0.3452 730 0.3510 744 0.3455 733 0.352 733 0.362 733 0.362 733 0.362 733 0.362 733 0.362 733 0.362 744 0.372 744 0.372 755 0.350 674 0.373 705 0.350 674 0.330 047 0.333 751 0.321 757 0.323 759 0.325 759 0.325 759 0.325 753 0.221 753 0.221 75368 0.211 778 0.213 5026 0.211 5368 0.214 4395 0.221 3866 0.214 4395 0.221 3866 0.214 4395 0.221 3866 0.214 4395 0.221 3866 0.214 4395 0.221 1386 0.214 4395 0.221 1386 0.214 7906 0.21 8536 0.21 1386 0	U TURB 47 27.458- 47 27.458- 69 24.923- 112 23.5091 113 22.525 119 22.3241 122 21.9761 1367 21.9761 165 22.839 109 23.745 104 24.572 115 26.746 115 26.772 115 26.772 115 26.772 115 28.941 115 28.941 115 28.941 115 28.941 115 28.941 115 28.941 115 14.972 115 14.972 115 14.971 115 13.91 115 13.71 14699 13.54 13.91 13.92 13.93 13.71 14692 13.91 1563 14.55	U W MEAN 46 -0.0323 42 -0.0705 59 -0.0651 11 -0.0552 59 -0.0253 59 -0.0253 50 -0.0253 50 -0.0253 50 -0.0253 50 -0.031 51 -0.032 57 -0.031 54 -0.021 53 -0.011 55 -0.021 55 -0.021 57 -0.031 54 -0.021 56 -0.021 56 -0.025 56 -0.021 56 -0.025 56 -0.021 56 -0.025 56 -0.025 57 -0.025 56 -0.025 57	W RMS 16 0.02305 16 0.02305 16 0.02305 16 0.1675 29 0.32524 57 0.30498 29 0.31425 57 0.32725 57 0.33527 35 0.33834 25 0.33834 25 0.33834 25 0.3383 26 0.32285 27 0.3248 26 0.3248 27 0.22859 28 0.2859 28 0.2859 28 0.2859 29 0.2639 39 0.2639 39 0.2639 39 0.2639 39 0.2639 39 0.2639 3052 0.172 352 0.164 424 0.1622 3732 0.164 424 0.1622 352	W TURBU 6 1.845259 8 4.063463 1 11.21945 3 21.19753 8 19.11568 5 19.33777 1 19.86316 6 20.63575 3 20.93215 3 20.9321	UW 0.000025 0.000025 0.000024 0.000024 0.000024 0.000024 0.000024 0.000024 0.003914 0.00459 0.007302 0.007306 0.002759 0.00121111 0.012747 0.006358 0.006453 0.006453 0.004453 0.004453 0.004453 0.004453 0.004453 0.004453 0.004453 0.000644 0.000644 0.000645 0.000645 0.000644 0.000645 0.000645 0.000645 0.000644 0.000645 0.000645 0.000647 0.000647 0.000647 0.000647 0.000537 0.000647 0.000536 0.000537 0.0	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 1.5 2 -1 1.5 -1 2.5 2 -1 -1 5 -1 2.5 2 -1 -1 5 -1 -1 5 -1 -1 5 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 5 -1 -1 5 -1 -1 5 -1 -1 5 -1 5 -1 5 -1 -1 -1 5 -1 -1 5 -1 -1 -1 5 -1 -1 -1 5 -1 -1 -1 5 -1 -1 -1 5 -1 -1 -1 5 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1	m/s	30 do	wnstred	am axi 	al velo	Incity	14 16 18 Radial (mm)

SHEAR STRESS AND TURBULENCE INTENSITY IN IN A CONCENTRIC ANNULAR ORIFICE



VELOCITY RAW DATA - SQUARE ORIFICE



SHEAR STRESS AND TURBULENCE INTENSITY IN SQUARE ORIFICE



VELOCITY RAW DATA - TRIANGULAR ORIFICE



SHEAR STRESS AND TURBULENCE INTENSITY IN TRIANGULAR ORIFICE



A. 4.4. Velocity data across different occluder positions

VELOCITY RAW DATA - CONCENTRIC ANNULAR ORIFICE

X L	ט כ	MEAN	UKM5 I	U TUKDU I	WMEAN Y	A KWD AA	TURBU UV		_		10 44			adal as	alacity		
1D dow	1 -	0.17763	0.546149	307,4663	-0.09059	0 062871	35,3948	-0.0018			10 00	whatr	ann a	XIAL Y	elocity		
stream	2	0.09713	0.540223	556,1886	-0 03758	0.066871 €	8.84695 -	0,00066	2.5 T	mla		1	prome				
	3	0.04198	0.58049	1382.839	-0.02329	0 123628	294.5047	-0.0054	2 +								- 1
	4 (0,162122	0,593131	365_8553	-0.04155	0.413768	255.2205	0.01104									1
	5 (261599	0.59163	226,1597	-0.05407	0.531864	203.3129	0.038/5	1.0 1				100				
	6 (.366684	0.594241	162.0581	-0_16807	0.547002	149 1753	0.07313	1 +				-				1
	7	0.34888	0.61817	177,1871	-0.25244	0.591151	169.4424	-0.09918	0.6		-B-m		1	8-A.		Radial (mm)
	8 (0.344105	0.653481	189 9075	-0.35448	0.618844	179.8416	-0.13521	0.5 T	11-18	-	8-8-	B-8	<u></u>	R. B.	64	
	9	242036	0.66919	276 4838	-0.3792	0.649657	268.4132	-0.15509	0+	-	-	+	+	PB.	-	-B-B	-
	10	0 107388	0.650112	605,3869	-0.34475	0.648602	603,9808	-0.14986	-050	2	10	8-8-		10	12	A 16	18
	11	0.018675	0.640627	3430.429	-0.28789	0 620767	3324.08	-0.11728	-0.0 T	B-8-8	-			- IL	18-18-		-0
	12	-0.15028	0.582681	387,7362	-0.08574	0.606888	403.8445	-0.07168	-1+						226		B8
	13	-0.285	0.535999	188,0683	0.057775	0.564718	198.1451	-0.03566	-151								- 1
	14	-0 34829	0.529583	152.054	0.127928	0.523177	150,2148	0.00592	-1.0								-
	4.5	0 47230	0.461189	97 62959	0.106085	0 487478	103,1948	0.028103 🖵	_			-		-			
	46	-0.47233	0.454433	78 82864	0.010319	0.466895	80.9903	0.018806									
	10	0.60858	0.427639	61 2156	-0.00558	0.403158	57.71122	0.007521									
	40	0.03030	0.376761	49 20232	-0.01289	0 379178	49.51797	0.006417									
~	18	-0./03/4	11 DMS	45 20232	WHEAN	WRMS I	N TURBU U	W									
X	0,1	J MEAN	U KMS	EC COLL	0.02202	0.020754	2 705893	0 000226		20	downe	tream	axial	veloc	ity pro	ofile	
2D dow	1	0.767004	0.434266	10.0211	-0.03393	0 17474	17 74812	-0.00377	25-		001110	(i çanı	graat				
stream	2	0.984557	0.491491	49 91997	-0,0618	0.17474	24 6127	-0.00526		m							
	3	1.110798	0.4602/3	41.4362	-0.05297	0 27 3397	24.0127	-0.00865	2	. 5			-8-8	-0-0			
	4	1.23115	0,4/6/92	30/2/30	-0.00403	0.30/300	30 36340	-0.01628	1.5						A. R.	-	1
	5	1.302208	0,493839	37.9232	-0.0/159	0 332318	30.30219	0.01620		1	10-B	-8-8	-8-6	-B-B	-81	10-10	
	6	1.339574	0.464899	34,70498	-0.06886	0.430128	34.1093	-0.01029	1.4		-	-0-0		-	11	Da-	R.
	7	1.355769	0.475957	35,10607	-0,09906	0.4410/	32.33282	-0.01922	0.5						-	a.	-
	8	1.37302	4 0,498839	36 33138	-0.1285	0,468518	34.12306	-0.03362			d.	020	5	2	10	- BAR	IL I
	9	1,375118	0.513429	37,33709	-0.19123	0.4/5335	34.56682	-0.05494	0				1	_			
	10	1.324220	5 0,509163	3 38.44986	-0,19235	0.475851	35.93427	-0.0484	-0.5	2	4	6	8	10	12	14 16	18
	11	1.23058	5 0.508396	5 41.31335	5 -0 15347	0.48343	39.28461	-0.05331								Radial	(mm)
	12	1.15167	5 0,49809	5 43 24963	-0.13668	0.480676	41.73715	-0.043	-1			190					
	13	1.01394	1 0.49301	8 48 6239	-0.08096	0,479898	47.33003	-0.03261	-1.5								
	14	0.87325	3 0.47899	5 54.85193	-0.04499	0,453271	51.90606	-0.01273									
	15	0.75503	6 0.44260	5 58 62034	0.01608	0.423506	56.09078	-0.00621							_		
	16	0.67101	7 0.44051	9 65 64941	0.00365	0.423998	63.18735	-0.02088									
	17	0.50388	7 0.42059	1 83 46922	2 0_038498	0.386643	76.73208	-0.01634									
	18	0.32052	1 0.37681	6 117.5638	8 0.034621	0.347594	108.4465	-0.00401									
x	D	U MEAN	URMS	U TURBU	W MEAN	WRMS	W TURBU	LIW .									
3d dow									_								
	1	1.24946	9 0.34304	7 27 45548	5 -0.03236	5 0.023056	1.845259	0.000026			3D do	ownsta	ream	axial 🛛	velocit	y .	
stream	1 2	1.24946	9 0.34304 9 0.34836	7 27 45548 9 24 98043	5 -0.03236 2 -0.07054	5 0.023056 1 0.056668	1.845259 4.063463	0.000026	2.5	Π.	3D do	wnsti	ream	axial v	velocit	Ŷ	
stream	1 2 3	1.24946 1.39456 1.49303	9 0.34304 9 0.34836 6 0.35101	7 27 45548 9 24 98043 2 23 5099	5 -0.03236 2 -0.07054 9 -0.06516	5 0.023056 4 0.056668 5 0.16751	1.845259 4.063463 11.21945	0.000026 0.000084 -0.00101	2.5	∏ m/s	3D do	wnsti	ream	axial	velocit	τ γ	
stream	1 2 3 4	1.24946 1.39456 1.49303 1.53434	9 0.34304 9 0.34836 6 0.35101 4 0.34561	7 27 45548 9 24 98043 2 23 50959 3 22 5251	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529	5 0 023056 4 0 056668 5 0 16751 9 0 325243	1.845259 4.063463 11.21945 21.19753	0.000026 0.000084 -0.00101 0.003914	2.5 2	m/s	3D do	ownsti	ream	axial y	velocit	γ L	
stream	1 2 3 4 5	1.24946 1.39456 1.49303 1.53434 1.59548	9 0.34304 9 0.34836 6 0.35101 4 0.34561 3 0.3561	7 27 45546 9 24 98043 2 23 5099 3 22 5251 9 22 3249	5 -0 03236 2 -0 07054 9 -0 06516 1 -0 05529 2 -0 04467	5 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988	1.845259 4.063463 11.21945 21.19753 19.11568	0.000026 0.000084 -0.00101 0.003914 0.00459	2.5 2 1.5	m/s	3D do	ownsti	ream 	axial v I-II-II		Y	200
stream	1 2 3 4 5	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508	9 0.34304 9 0.34836 6 0.35101 4 0.34561 3 0.3561 36 0.35726	7 27 45546 9 24 9804 2 23 5099 3 22 5251 9 22 3249 2 21 9842	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529 2 -0.04467 2 -0.04309	5 0 023056 4 0 056668 5 0 16751 9 0 325243 7 0 304988 9 0 314255	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777	0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302	2.5 2 1.5	m/s	3D do	ownsti 9-9-1 9-0-1 9-0-1	ream 9-19-1 9-19-1 9-19-1	axial y 	velocit		·
stream	1 2 3 4 5 6 7	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 13 0.35726 29 0.36206	7 27 45546 9 24 98043 2 23 50999 3 22 5251 9 22 3249 2 21 9842 7 21 9753	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529 2 -0.04467 2 -0.04309 5 -0.0292	5 0 023056 4 0 056668 5 0 16751 9 0 325243 7 0 304988 9 0 314255 7 0 327251	1.845259 4.063463 11,21945 21.19753 19,11568 19,33777 19,86316	0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306	2.5 2 1.5	m/s	3D dd	ownsti 0-0-1 0-0-1	ream 	axial 			
stream	1 2 3 4 5 6 7	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64752	9 0.34304 9 0.34836 6 0.35101 14 0.34561 33 0.3561 36 0.35726 29 0.36206	7 27 45540 9 24 98043 2 23 5099 3 22 5251 9 22 3249 2 21 9842 37 21 9763	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529 2 -0.04467 2 -0.04309 5 -0.0297 7 -0.02594	5 0 023056 4 0 056668 5 0 16751 9 0 325243 7 0 304988 9 0 314255 7 0 327251 4 0 335276	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579	0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306 0.006759	2.5 2 1.5 1 0.5	m/s	3D do	ownsti 9-9-1 9-0-1 9-8-1	ream 9-9-1 9-0-1 9-0-1	axial - D-O-1 D-O-1	velocit		
stream	1 2 3 4 5 6 7 8	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.62508 1.64752 1.62473	9 0.34304 9 0.34836 6 0.35101 4 0.34561 3 0.3561 3 0.35726 29 0.36206 3 0.36290 3 0.36290	7 27 4554(9 24 9804) 2 23 5099 3 22 5251 9 22 3249 2 21 9842 57 21 9763 6 22 3363	5 -0 03236 2 -0 07054 9 -0 06516 1 -0 05529 2 -0 04467 2 -0 04309 5 -0 0297 7 -0 02594 2 -0 01339	 0 023056 0 056668 0 16751 0 325243 0 304988 0 314255 0 327251 0 335276 0 338343 	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215	0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111	2.5 2 1.5 1 0.5	m/s	3D dd	ownsti 0-0-1 0-0-1	ream 	axial v B-B-q D-D-q B-B-q	velocit	Y La la la La la	122
stream	1 2 3 4 5 6 7 8 9	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64752 1.62473 1.61633	9 0,34304 9 0,34836 6 0,35101 14 0,34561 33 0,3561 36 0,35726 29 0,36206 33 0,36290 79 0,36916 79 0,36916	7 27.4554(9 24.9804) 2 23.5099(3 22.5251 9 22.3249) 2 21.9842 37 21.9763 36 22.3363 35 22.8360 29 24.850	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529 2 -0.04467 2 -0.04309 5 -0.0297 7 -0.02594 2 -0.01333 7 -0.01381 7 -0.01	 0.023056 0.056668 0.16751 0.325243 0.304988 0.314255 0.327251 0.335276 0.338343 0.338343 0.338343 	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811	0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111 0.012747	2.5 2 1.5 1 0.5 0	m/s	3D do	ownsti 	ream 	axial v B-B-q B-D-q B-D-q B-B-q A			
stream	1 2 3 4 5 6 7 8 9 10	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64752 1.64752 1.61633 1.57504	9 0.34304 9 0.34836 6 0.35101 14 0.34561 30 0.3561 6 0.35726 29 0.36206 33 0.36290 79 0.36916 47 0.37400	7 27.4554(9 24.9804) 2 23.5099(3 22.5251) 9 22.3249 (2 1.9842) 7 21.9763 (6 22.3363) 5 22.8390 (9 23.7458) 2 2.7458 2 2.7458	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05525 2 -0.04467 2 -0.04305 5 -0.0297 7 -0.02594 2 -0.0138 4 -0.0138	 0.023056 0.056668 0.16751 0.325243 0.304988 0.3142557 0.327251 0.335276 0.338342 	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.151811	0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358	2.5 2 1.5 1 0.5 0 -0.5	m/s	3D do	ownsti 	ream 	axial y B-B-q D-D-q D-D-q 10	velocit	14 16	6 18
stream	1 2 3 4 5 6 7 8 9 10 11	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64752 1.62473 1.61633 1.57504 1.51714	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 16 0.35726 19 0.36206 13 0.36290 79 0.36916 47 0.37400 44 0.37280	7 27.4554(9 24.9804) 2 23.5099 3 22.5251 9 22.3249 2 21.9842 3 21.9763 6 22.3363 5 22.8350 9 23.7458 04 24.5727	6 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02937 7 -0.02534 2 -0.01333 7 -0.01383 4 -0.04001	0.023056 0.056668 0.056668 0.325243 0.325243 0.304988 0.314255 0.327251 4.0335276 5.0338343 5.0338343 6.0338574 6.0335276	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855	0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358	2.5 2 1.5 1 0.5 0 -0.5	m/s	3D do	ownsti 	ream 	axial y 	velocit	14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 7 8 9 10 11 12	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64752 1.62473 1.61633 1.57504 1.51714 1.51714	9 0,34304 9 0,34836 6 0,35101 4 0,34561 3 0,3561 6 0,35726 9 0,36290 79 0,36916 47 0,37400 44 0,37280 51 0,3783	7 27.4554(9 24.9804) 2 23.50951 9 22.5251 9 22.3249 9 22.3249 2 21.9842 7 21.9763 6 22.3363 5 22.8390 9 23.7458 04 24.5727 15 26.7765	5 -0.03236 2 -0.07054 9 -0.05529 2 -0.04467 2 -0.04305 5 -0.0297 7 -0.02594 2 -0.01333 7 -0.01383 4 -0.04004 5 -0.03211 -0.03211 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.03212 -0.04467 -0.04467 -0.02917 -0.02917 -0.03216 -0.03	0.023056 0.056668 0.056668 0.325243 0.325243 0.3304988 0.314255 0.327251 4.0335276 5.0383433 5.033832 6.0338374 5.032874 6.032874 6.032874 7.032852 7.032852	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41953	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007305 0.012111 0.012747 0.006358 0.009453 0.009453	2.5 2 1.5 1 0.5 0 -0.5 -1	m/s	3D do	e e f	ream 	axial y 	velocit	14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 7 8 9 10 11 12 13	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64755 1.62475 1.62475 1.61633 1.57504 1.51714 1.41289 1.3289	9 0,34304 9 0,34836 6 0,35101 14 0,34561 3 0,3561 9 0,36290 79 0,36916 47 0,37400 14 0,37280 51 0,3783 57 0,3733	7 27.4554(9 24.9804) 2 23.50951 9 22.5251 9 22.3249 9 22.3249 2 21.9842 7 21.9763 6 22.3363 5 22.8390 9 23.7458 04 24.5727 15 26.7765 73 28.0945	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04303 5 -0.02597 7 -0.02597 2 -0.01333 7 -0.01388 4 -0.04000 11 -0.03211 -0.03211 -0.03100	0.023056 0.056668 0.305668 0.304988 0.314255 0.327251 0.338343 0.338343 0.338343 0.33827 0.33827 0.33827 0.33827 0.33827 0.33827 0.33827 0.33827 0.322852 1.032455 0.322852 1.032455	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.441863 2.441863	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007305 0.012111 0.012747 0.006358 0.009453 0.004007	2.5 - 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	evensti e	ream 	axial y 	velocit	Y 14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 7 8 9 10 11 12 13 14	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.62473 1.62473 1.62473 1.62473 1.62473 1.62473 1.62473 1.62473 1.62509 1.62473 1.5750 1.51711 1.41289 1.3289 1.2437	9 0,34304 9 0,34336 66 0,35101 14 0,3451 13 0,3510 14 0,3451 13 0,3510 14 0,3451 13 0,3510 14 0,3561 13 0,3521 14 0,36216 15 0,36216 16 0,37400 14 0,37280 15 0,37283 16 0,37333 17 0,37333	7 27.4554(9 24.9804(: 2 23.5099(: 3 22.5251 9 22.3249(: 92 21.9842(: 77 21.9763(: 96 22.323(: 97 21.9763(: 98 22.323(: 99 23.7458(: 90 23.7458(: 91 24.5727(: 92 28.990(: 73 28.0945(: 55 28.2165(:	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04467 2 -0.04303 5 -0.0293 7 -0.02334 2 -0.01384 4 -0.04000 5 -0.03211 57 -0.0310 54 -0.0210	0.023056 0.056668 0.16751 0.325243 7.0304988 0.314255 7.0327251 4.0335276 5.0338342 6.0338342 6.0338342 6.0338342 6.0338574 7.032452 1.032452 2.0309702 2.0309702 2.0309702	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 2.2.85093 2.4.41863 3.24.90168	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.009453 0.004007 0.005538	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	evensti	ream 	axial D-D- D-D- D-D- D-D- 10	velocit	y 14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15	1.24946 1.39456 1.49303 1.59546 1.62508 1.62508 1.64752 1.62477 1.61633 1.5750 1.5171 1.41288 1.3289 1.24370 1.24370 1.2456	9 0.34304 9 0.34836 6 0.35101 13 0.3561 13 0.3526 13 0.3526 13 0.3526 13 0.3526 13 0.36296 14 0.37400 14 0.37286 15 0.37833 16 0.37833 17 0.37333 10 0.37337 10 0.3509 14 0.3307	7 27,45544 9 24,98044 2 23,5099 3 22,5251 9 22,3249 22,3249 22,3249 22,3363 5 22,8350 9 23,7458 34 24,5727 5 26,7765 5 28,2185 55 28,2185 55 28,2185 55 29,385 56 29,385 57 30,945 56 29,385 57 30,945 57 30,945 50 30,9	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02397 7 -0.02597 2 -0.01333 7 -0.02594 1 -0.03211 1 -0.03211 1 -0.03211 1 -0.0216 1 -0.0216	0.023056 0.023056 0.056668 0.305668 0.325243 0.304988 0.314255 0.335276 0.335276 0.338326 0.335874 0.335276 0.33892 0.335874 0.322852 1.032452 4.0309703 9.028592 0.309703 9.028592	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 3 24.90168 3 25.40058	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.004007 0.005538	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	6	ream 	axial	12	Y 14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16	1.24946 1.39456 1.49303 1.59548 1.62508 1.62508 1.64752 1.62477 1.6163 1.5750 1.5171 1.4128 1.3289 1.2437 1.1256 5.10290	9 0.34304 9 0.34836 6 0.35101 14 0.34631 13 0.3561 13 0.35226 13 0.36290 13 0.36290 13 0.36291 14 0.37400 14 0.3726 15 0.37331 16 0.37331 17 0.37331 187 0.35091 174 0.33071 147 0.32341	7 27,45544 9 24,98044 9 24,98044 2 23,5099 3 22,5251 9 22,3249 12 21,9763 12 21,9763 15 22,3363 15 22,8390 19 23,7458 14 24,5727 15 26,7765 15 28,2185 15 28,2185 15 28,2185 15 28,2185 15 28,2185 15 28,2185 15 28,2185 15 28,2185 15 28,2185 15 28,2185 15 28,2185 16 31,4296 17 28,3145	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.01333 7 -0.01383 4 -0.04001 51 -0.0310 52 -0.01383 53 -0.0310 54 -0.0310 54 -0.01313 54 -0.01310	0.023056 0.056668 0.305668 0.304988 0.314255 0.335276 0.335276 0.338343 0.338343 0.338843 0.338844 0.338844 0.338844 0.338844 0.338844 0.338844 0.338844 0.322852 4.032852 0.328524 0.328522 8.0289032 0.289032 0.289032	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.441863 2.4.90168 3.24.90168	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.009453 0.004943	2.5 2 1,5 1 0,5 0 -0,5 -1 -1,5	m/s	3D do	e e f	ream 	axial	12	Y 14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64753 1.624753 1.624753 1.624753 1.624753 1.624753 1.57500 1.57710 1.51710 1.517500 1.51710 1.52899 1.24396 1.24396 1.24396 1.24396 1.24396 1.24396 1.24396 1.57500 1.51710 1.5126 1.5226 1.52666 1.52666 1.52666 1.52666 1.52666	9 0.34304 9 0.34836 6 0.35101 14 0.34631 13 0.3561 13 0.3561 13 0.35262 13 0.36290 13 0.36290 14 0.37400 14 0.37400 14 0.37400 14 0.37400 14 0.37400 15 0.37400 16 0.37400 17 0.37400 18 0.37400 19 0.37400 10 0.37833 10 0.37833 10 0.35091 10 0.32041 14 0.32041	7 27,45544 9 24,98043 2 23,50993 3 22,5251 9 22,3249 12 21,9763 36 22,3830 55 22,8390 9 23,7458 04 24,5727 15 26,7765 73 28,0945 52 29,383 26 31,4296 26 36,035	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02597 2 -0.01333 7 -0.02597 2 -0.04305 4 -0.04305 5 -0.01333 4 -0.04000 5 -0.0310 64 -0.0216 55 -0.0216 54 -0.0216 55 -0.0113 67 0.00878 64 0.01075	0.023056 0.056668 0.305668 0.304988 0.314255 0.327251 0.338343 0.338343 0.338343 0.322652 1.0322652 0.338574 0.338343 0.338243 0.338243 0.338574 0.322652 1.0324552 0.309703 9.0285921 0.285921 0.287903 4.028780	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 3 24.90168 3 24.90168 3 25.40058	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.006759 0.012111 0.012747 0.006358 0.009453 0.004007 0.005528 0.003384 0.004943 0.007151	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	e e f	8	axial	12	Y 14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64752 1.62473 1.57500 1.57714 1.41289 1.22437 1.41289 1.22437 1.1.2566 1.02907 0.8927 3 0.7171	9 0.34304 9 0.34836 6 0.35101 14 0.34836 13 0.3561 13 0.3561 13 0.3561 13 0.3561 13 0.3561 14 0.34836 15 0.36296 16 0.37400 17 0.37400 14 0.37400 14 0.37400 15 0.37400 16 0.37400 17 0.37400 10 0.37433 10 0.37333 10 0.35092 11 0.32347 10 0.32347 10 0.32347 10 0.32347	7 27,45544 9 24,98043 2 23,50993 3 22,5251 9 22,3249 9 22,3263 9 22,3363 9 22,3363 9 22,3363 9 23,7458 9 24,5727 15 26,7765 73 28,0945 55 22,9383 26 31,4296 26 34,6035 26 34,6035 26 36,0335 27 36,0335	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 7 -0.01333 7 -0.01334 7 -0.03211 77 -0.0310 54 -0.0213 70 -0.0310 55 -0.0211 70 -0.0310 54 -0.0213 70 -0.0310 54 -0.0213 70 -0.0310 54 -0.0213 77 -0.0310 54 -0.0213 77 -0.0310 54 -0.0213 77 -0.0310 54 -0.0213 70 -0.04133 70 -0.04133 70 -0.02134 70 -0.04133 70 -0.04133 70 -0.04133 70 -0.04133	0.023056 0.056668 0.056688 0.16751 0.325243 0.304988 0.314255 7.0.327251 4.0.335276 0.338343 5.0.338343 5.0.33824 0.322652 1.0.322652 1.0.32455 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926 9.0.285926	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.93215 21.51811 22.13855 22.85093 24.41863 3 24.90168 5 25.40058 5 28.08762	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007305 0.002750 0.012111 0.012747 0.006358 0.009453 0.004007 0.005558 0.00384 0.003384 0.003384	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do		ream 	axial	12	Y 14 16 Radial	5 18 (mm)
stream	1 2 3 4 5 6 6 7 8 9 10 11 12 13 14 15 16 17 18 16 17 18 10 17 18 10 17 18 10 19 10 10 10 10 10 10 10 10 10 10 10 10 10	1.24946 1.39456 1.49306 1.53434 1.59548 1.62508 1.64757 1.6163 1.57504 1.57504 1.57504 1.57504 1.57504 1.57504 1.24376 1.32895 1.24376 1.24376 1.2266 1.02907 0.8927 0.7771 U MEAN	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 16 0.35726 29 0.36206 17 0.37400 14 0.37280 10 0.3783 1 0.3783 1 0.3783 1 0.3783 1 0.3783 1 0.3214 1 0.3214 1 0.3214 1 0.3214 1 0.3214 1 0.3267 1 0.327 1 0.3267 1 0.3267 1 0.327 1 0.3267 1 0.327 1 0.37	7 27,45544 9 24,98043 2 23,50959 3 22,5251 9 22,3249 22 32,9249 22 32,9249 22 32,9249 22 32,9249 22 32,9249 23 7458 35 22,8350 39 23,7458 34 24,5727 55 28,2185 55 28,2185 55 28,2185 55 28,2185 55 28,2185 56 29,362 56 4,65582 0 UTURB	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529 2 -0.04467 2 -0.04305 5 -0.0297 7 -0.0259 2 -0.0133 7 -0.03219 1 -0.03211 37 -0.0310 34 -0.0216 35 -0.0113 34 -0.0216 35 -0.0113 34 -0.0216 35 -0.0113 34 -0.0216 35 -0.0113 34 -0.0216 35 -0.0113 34 -0.0216 35 -0.0113 34 -0.0216 35 -0.0113 37 -0.00878 40 -0.00878 40 -0.0053 40 -0.053 40 -0	0.023056 0.023056 0.056668 0.305668 0.325243 0.325243 0.334255 0.335276 0.335276 0.338326 0.335874 0.335276 0.335874 0.335874 0.335874 0.335874 0.335874 0.322852 1 0.32452 4 0.309703 9 0.285921 8 0.289032 9 0.289324 9 0.263924 9 0.263924 9 0.263924 9 0.263924 9 0.263924 9 0.263924 9 0.263924	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 2.285093 2.4.41863 3.24.90168 3.24.90168 3.24.90168 3.25.40058 5.36.80275 W TURBU	0.000025 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	ownstr 	Barn C	axial v	12	14 10 Radial	5 18 (mm)
stream × 6d dov	1 2 3 4 5 6 6 6 7 7 8 9 9 10 11 11 12 13 14 15 14 15 14 15 14 15 16 17 18 17 18 19 19 10 10 11 11 11 11 11 11 11 11 11 11 11	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64753 1.624753 1.61633 1.57500 1.51711 1.41289 1.2437 5 1.2256 5 1.0290 7 0.8927 8 0.7171 U MEAN 1.3157	9 0.34304 9 0.34836 6 0.35101 14 0.34631 13 0.3561 14 0.34631 13 0.35226 13 0.36290 14 0.36290 15 0.36291 16 0.37831 17 0.37400 14 0.37831 15 0.35091 14 0.33070 14 0.32141 10 0.32341 10 0.32741 10 0.32141 10 0.32141 11 0.32141 12 0.32141 13 0.32141 14 0.32141 15 0.32167 14 URMS 179 0.3756	7 27,45544 9 24,98044 9 24,98044 2 23,5099 3 22,5251 9 22,3249 12 21,9763 12 21,9763 15 22,8390 15 22,7765 15 28,7765 15 28,7765 15 28,7165 15 28,7165 15 28,2185 15 28,2185 15 28,31429 16 31,4296 17 29,383 18 36,033 19 31,4296 10 31,4296 10 31,4296 11 28,5496	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.01338 7 -0.0259 2 -0.01388 4 -0.04001 5 -0.0310 5 -0.01388 4 -0.03201 5 -0.01388 4 -0.0310 5 -0.0113 6 -0.0216 35 -0.0113 36 -0.0053 21 -0.00533 U W MEAN 59 -0.0618	6 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 5 0.335276 6 0.338343 5 0.338843 5 0.338844 5 0.332852 4 0.302452 4 0.302452 4 0.302452 4 0.302452 4 0.322452 4 0.32452 4 0.328926 8 0.289033 44 0.287800 9 0.263920 1 W RMS 88 0.10608	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.24.41863 2.4.90168 3.24.90168 3.24.90168 5.28.08762 5.36.0275 W TURBU 1.8.662186	0.000025 0.000084 0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.004943 0.004943 0.004943 0.004943 0.004943 0.004955 UW	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	ownstr 	am a:	axial v	12	Y 14 16 Radial	5 18 (mm)
stream Sd dov stream	1 2 3 4 5 6 6 6 7 7 8 9 9 10 11 11 12 13 14 15 14 15 14 15 14 15 16 17 18 17 18 17 18 19 10 10 11 11 11 12 13 14 15 10 10 10 10 10 10 10 10 10 10 10 10 10	1.24946 1.39456 1.49303 1.53434 1.59548 1.62506 1.64753 1.624753 1.61633 1.57504 1.51714 1.41289 1.23775 1.22565 1.02907 0.8927 3.0.7714 UMEAN 1.3157 2.1.4609	9 0.34304 9 0.34836 6 0.35101 14 0.3451 13 0.3561 13 0.3561 13 0.35226 13 0.36290 13 0.36290 14 0.37400 14 0.37400 14 0.37400 14 0.37400 14 0.3733 15 0.35099 74 0.33070 147 0.32343 151 0.3214 136 0.3367 147 0.33071 147 0.3243 151 0.3214 136 0.3367 147 0.3756 153 0.2321	7 27,45544 9 24,98043 9 24,98043 2 23,50993 3 22,5251 9 22,3249 12 21,9763 12 21,9763 12 21,9763 12 23,363 15 22,8390 15 26,7765 15 28,2185 15 28,2185 15 28,2185 16 21,9383 16 31,4296 17 31,4296 16 36,6033 17 28,5496 10 UTURB 11 28,5496 11 15,894	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.01333 7 -0.02594 2 -0.01333 7 -0.02133 4 -0.04004 11 -0.0310 35 -0.0113 367 0.00268 34 0.01075 21 -0.00533 40 0.00755 21 -0.00536 359 -0.0618 44 -0.0250	0.023056 0.056668 0.305668 0.304988 0.314255 0.332726 0.338343 5 0.338343 5 0.338343 5 0.322521 0.328521 0.324521 0.324521 0.324521 0.324521 0.324521 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.3245221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221 0.2285221	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.43503 24.41863 3 24.90168 3 24.90168 3 25.40058 5 28.08762 4 32.23788 5 36.80275 W TURBU 1 8.062186 8 0.817825	0.000025 0.000084 0.00084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.006358 0.009453 0.009453 0.004943 0.004943 0.004943 0.0010675 0.010675 0.010675 0.010675 0.010675 0.010675 0.010675 0.010675	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5	m/s	3D do	e e e e e e e e e e e e e e e e e e e	sam a	axial v	12	y 14 16 Radial	5 18 (mm)
stream 6d dov stream	1 2 3 4 5 5 6 6 7 7 8 9 9 10 11 11 12 13 14 15 16 16 17 18 18 18 18 18 18 18 18 18 18 18 18 18	1.24946 1.39430 1.49430 1.53434 1.59548 1.62508 1.62473 1.62473 1.62473 1.62473 1.62473 1.62473 1.62473 1.62473 1.62473 1.41289 1.24376 1.2256 5 1.0290 0.8327 3 0.7171 U MEAN 1.3157 2 1.4609 3 1.5057	9 0.34304 9 0.34836 66 0.35101 14 0.34836 13 0.3561 13 0.3561 13 0.3561 13 0.3561 13 0.3561 14 0.34836 15 0.36290 16 0.37400 17 0.37400 14 0.37400 14 0.37333 15 0.37333 16 0.33077 17 0.32343 16 0.32343 17 0.32344 18 0.33077 14 U.BM3 13 0.3756 14 U.BM3 14 U.BM3 15 0.2217 18 0.2217	7 27,45544 9 24,98043 9 24,98043 2 23,50993 3 22,5251 9 22,3249 12 21,9763 36 22,3839 35 22,8390 36 22,3839 37 28,0445 36 22,383 31 24,5727 32 28,2185 32 29,383 32 29,383 32 29,383 36 31,4296 36 34,4296 36 36,035 54 46,9532 54 46,9532 51 28,5496 1 15,899 99 14,7296	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02597 2 -0.01333 7 -0.02594 2 -0.01333 7 -0.02136 5 -0.0310 64 -0.0216 55 -0.0113 67 -0.0216 63 -0.0216 64 -0.0216 63 -0.00175 21 -0.00618 94 -0.00105 95 -0.00618 44 -0.0250 55 -0.0255	6 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3037251 6 0.338343 5 0.338343 5 0.338242 6 0.335276 6 0.338242 7 0.3027652 1 0.322652 1 0.32452 4 0.309703 6 0.23921 8 0.263922 1 WRMS 88 0.10608 90 0.243921	1.845259 4.063463 11,21945 21,19753 19,11568 19,33777 19,86316 20,63579 20,93215 21,51811 22,13855 22,85093 24,41863 24,40168 32,23788 536,80275 W TURBU 8,062186 60,817825 40,842313	0.000025 0.000026 0.00084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007305 0.0021111 0.012747 0.006358 0.004007 0.005538 0.004007 0.005538 0.003844 0.0009433 0.0007151 0.010675 uw 3 -0.00188 0.000064 -4.8E-05	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2	m/s	3D do	e e e e e e e e e e e e e e e e e e e	am a	axial v	12	14 16 Radial	5 18 (mm)
stream 6d dov stream	1 2 3 4 5 6 6 7 7 8 9 9 10 11 11 12 13 14 15 16 17 18 18 19 10 11 11 12 13 14 15 16 17 17 18 19 10 10 11 11 12 13 10 10 11 11 12 10 10 10 11 11 11 11 11 11 11 11 11 11	1.24946 1.39456 1.49303 1.53434 1.59544 1.62508 1.64753 1.62477 1.61633 1.5750 1.51714 1.41286 1.3289 1.24376 1.3256 5 1.0290 0.7171 U MEAN 1.3157 2 1.4605 3 1.50548	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 16 0.35726 29 0.36206 17 0.37400 14 0.37280 10 0.3783 10 0.3783 10 0.3783 10 0.3214 31 0.3214 31 0.3214 36 0.3367 4 U RM3 79 0.3756 53 0.2217 186 0.2172	7 27,45544 9 24,98043 2 23,50959 3 22,5251 9 22,3249 12 21,9763 12 21,9763 12 21,9763 12 21,9763 12 22,3233 15 22,7755 15 26,7765 15 28,2185 15 28,2185 15 28,2185 15 28,2185 14 24,5727 15 28,2185 15 28,2185 14 24,5727 12 28,346 14 24,5727 12 28,362 13 15,894 13 97,31	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02937 7 -0.02597 2 -0.01333 7 -0.02597 1 -0.0310 64 -0.04305 1 -0.03211 67 -0.003211 64 -0.01333 67 -0.003211 64 -0.01075 21 -0.00053 U W MEAN 59 -0.0255 92 -0.03053	0.023056 0.023056 0.056668 0.305668 0.304988 0.314255 0.325243 7 0.304988 0.314255 0.335276 0.338326 0.33892 0.33882 0.33882 0.33892 0.33892 0.33892 0.33892 0.33892 0.33892 0.33892 0.33892 0.332852 0.309703 9.285921 8.028032 9.0285921 8.028032 9.0285921 8.028032 9.0285921 8.028032 9.028932 9.028932 8.0010608 8.0010608 8.0010608 8.0010608 8.0010608 8.0010608 8.0010608 8.001268 9.02396	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.4.41863 2.4.90168 3.24.90168 3.24.90168 3.25.40058 5.36.80275 W TURBU 1.8.062186 8.0817825 4.0.817855 4.0.81785556 4.0.8178556 4.0.8178556 4.0.81785566 4.0.8178556666666666666666666666666666666666	0.000025 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.004943 0.004943 0.004943 0.0004943 0.0007151 0.010675 UW 0.000064 0.000064 0.000064 0.000064 0.000064	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2	m/s	3D dc	e e f	am a:		12	y 14 16 Radial	5 18 (mm)
stream 6d dov stream	1 2 3 4 5 6 6 7 7 8 9 9 10 11 11 12 13 14 15 16 17 18 16 17 18 16 17 18 18 18 18 18 18 18 18 18 18 18 18 19 19 10 10 11 11 12 10 10 10 10 10 10 10 10 10 10 10 10 10	1.24946 1.39456 1.49300 1.53434 1.59548 1.62506 1.64752 1.61633 1.57504 1.51714 1.41286 1.22837 1.2256 1.02907 0.8927 0.7171 UMEAN 1.31572 1.4609 3.1.5578 1.5577	9 0.34304 9 0.34836 6 0.35101 14 0.3451 13 0.3521 13 0.3522 13 0.3522 13 0.3522 13 0.3522 14 0.34836 15 0.3522 16 0.35726 17 0.36290 18 0.37831 19 0.37831 10 0.37831 10 0.37831 10 0.32144 10 0.32144 10 0.32144 10 0.32741 13 0.32144 13 0.32132 147 0.32132 150 0.2217 160 0.2112	7 27,45544 9 24,98044 9 24,98044 2 23,5099 3 22,5251 9 22,3249 12 21,9763 12 21,9763 15 22,8390 15 22,7765 15 28,7765 15 28,7765 15 28,7165 15 28,2185 15 28,2185 15 28,2185 15 28,31429 16 31,4296 17 21,9763 18 36,0355 19 14,7294 26 36,0355 10 UTURB 51 28,5496 21 15,899 99 14,7297 13,5736 13,516	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.01338 7 -0.0259 2 -0.01388 4 -0.04001 5 -0.01138 7 -0.0310 54 -0.0216 35 -0.01133 7 -0.00532 21 -0.00532 21 -0.00535 21 -0.00535 20 -0.0256 55 -0.0256 55 -0.0256 55 -0.0256 55 -0.0256 55 -0.0256 55 -0.0256 59 -0.03026 59 -0.03026 59 -0.03026 59 -0.03026 59 -0.03026 59 -0.03026 59 -0.03026 <td>0.023056 0.0023056 0.056668 0.305668 0.304988 0.314255 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.322852 0.322852 0.328526 0.328526 0.328526 0.328926 0.285926 8.0289033 4.0309703 9.0285926 8.0289033 4.0309703 9.0285926 8.0289033 4.0309703 9.0285926 8.010608 9.0285927 8.010608 9.020392 9.020392 9.020392 9.020392 9.02392 9.02392 9.02392 9.02392 9.02392 0.073871 </td> <td>1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.4.41863 3.24.90168 3.2</td> <td>0.000025 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.004943 0.004943 0.004943 0.004943 0.000488 0.000068 0.000068 0.000068 0.000068 0.000068 0.000068 0.000068</td> <td>2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5</td> <td>m/s</td> <td>3D dec</td> <td>e e e e e e e e e e e e e e e e e e e</td> <td>Barna a</td> <td>axial ve</td> <td>12</td> <td>y 14 16 Radial</td> <td>5 18 (mm)</td>	0.023056 0.0023056 0.056668 0.305668 0.304988 0.314255 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.322852 0.322852 0.328526 0.328526 0.328526 0.328926 0.285926 8.0289033 4.0309703 9.0285926 8.0289033 4.0309703 9.0285926 8.0289033 4.0309703 9.0285926 8.010608 9.0285927 8.010608 9.020392 9.020392 9.020392 9.020392 9.02392 9.02392 9.02392 9.02392 9.02392 0.073871	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.4.41863 3.24.90168 3.2	0.000025 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.004943 0.004943 0.004943 0.004943 0.000488 0.000068 0.000068 0.000068 0.000068 0.000068 0.000068 0.000068	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5	m/s	3D dec	e e e e e e e e e e e e e e e e e e e	Barna a	axial ve	12	y 14 16 Radial	5 18 (mm)
stream 6d dov stream	1 2 3 4 5 6 6 7 7 8 9 9 100 111 122 133 144 155 160 111 122 133 144 155 160 7 7 8 9 9 9 100 7 7 8 8 9 9 100 111 122 5 6 6 7 7 8 8 9 9 100 111 122 5 7 7 8 8 9 9 100 111 1122 1132 1122 1122 1122 1122 1	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64753 1.624753 1.624753 1.61633 1.57504 1.51714 1.41289 1.24375 1.24375 1.24375 1.24375 1.24375 1.51576 1.51575 1.55485 1.55585 1.55585 1.555785 1.555855 1.55585 1.55585 1.555855 1.555855 1.555855 1.555	9 0.34304 9 0.34836 9 0.34836 6 0.35101 13 0.3561 13 0.3561 13 0.35226 13 0.36290 13 0.36290 14 0.37400 14 0.37400 14 0.37331 10 0.37331 10 0.37331 10 0.32341 13 0.3214 14 0.33070 15 0.3214 16 0.3232 17 0.3756 18 0.2217 186 0.2217 186 0.2132 126 0.2132 127 0.2132 128 0.2132 129 0.2132 120 0.2173	7 27,45544 9 24,98043 2 23,5099 3 22,5251 9 22,3249 12 21,9763 12 21,9763 12 21,9763 12 21,9763 14 24,9727 15 26,7765 15 28,9462 28,9462 29,383 26 31,4296 26 36,6032 26 36,6032 26 36,6032 27 15,894 99 14,7294 99 14,7294 99 14,7293 38 13,711	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.01333 7 -0.02594 2 -0.01338 4 -0.04001 16 -0.0310 17 -0.0310 16 -0.0216 35 -0.0113 367 0.00878 34 0.01075 21 -0.00505 59 -0.0618 44 -0.0250 55 -0.0250 59 -0.0618 44 -0.0250 59 -0.0310 77 -0.0668 92 -0.0305 77 -0.04250 592 -0.0350 92 -0.04250 92 -0.04250 93 -0.04250 94 -0.04250 95 -0.02514 <td>6 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 6 0.335276 5 0.338343 5 0.338343 5 0.338242 1 0.32452 4 0.302952 1 0.32452 4 0.309703 9 0.285926 8 0.209732 9 0.228522 8 0.209736 9 0.228522 8 0.208780 9 0.228522 8 0.10608 9 0.228392 9 0.228392 9 0.228392 9 0.228392 9 0.22392 9 0.22392 9 0.22392 9 0.22392 9 0.17869 <td>1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.40583 24.41863 3 24.90168 3 24.90168 3 25.40058 5 28.08762 4 32.23788 5 36.80275 W TURBU 1 8.062188 8 0.817825 4 0.842313 1 1.54100 4 4.98887(1 11.2736)</td><td>0.000025 0.000084 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.002558 0.002453 0.004538 0.004538 0.004553 0.0044007 0.005258 0.00384 0.004943 0.000453 0.000188 0.000064 3 0.000064 3 0.000086 0.000188</td><td>2.5 2 1,5 1 0,5 0 -0,5 -1 -1.5 2.5 2 1.5 2 1.5</td><td>m/s</td><td>3D dec</td><td>e e e</td><td>am a</td><td>axial v </td><td>12</td><td>y 14 16 Radial</td><td>5 18 (mm)</td></td>	6 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 6 0.335276 5 0.338343 5 0.338343 5 0.338242 1 0.32452 4 0.302952 1 0.32452 4 0.309703 9 0.285926 8 0.209732 9 0.228522 8 0.209736 9 0.228522 8 0.208780 9 0.228522 8 0.10608 9 0.228392 9 0.228392 9 0.228392 9 0.228392 9 0.22392 9 0.22392 9 0.22392 9 0.22392 9 0.17869 <td>1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.40583 24.41863 3 24.90168 3 24.90168 3 25.40058 5 28.08762 4 32.23788 5 36.80275 W TURBU 1 8.062188 8 0.817825 4 0.842313 1 1.54100 4 4.98887(1 11.2736)</td> <td>0.000025 0.000084 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.002558 0.002453 0.004538 0.004538 0.004553 0.0044007 0.005258 0.00384 0.004943 0.000453 0.000188 0.000064 3 0.000064 3 0.000086 0.000188</td> <td>2.5 2 1,5 1 0,5 0 -0,5 -1 -1.5 2.5 2 1.5 2 1.5</td> <td>m/s</td> <td>3D dec</td> <td>e e e</td> <td>am a</td> <td>axial v </td> <td>12</td> <td>y 14 16 Radial</td> <td>5 18 (mm)</td>	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.40583 24.41863 3 24.90168 3 24.90168 3 25.40058 5 28.08762 4 32.23788 5 36.80275 W TURBU 1 8.062188 8 0.817825 4 0.842313 1 1.54100 4 4.98887(1 11.2736)	0.000025 0.000084 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.002558 0.002453 0.004538 0.004538 0.004553 0.0044007 0.005258 0.00384 0.004943 0.000453 0.000188 0.000064 3 0.000064 3 0.000086 0.000188	2.5 2 1,5 1 0,5 0 -0,5 -1 -1.5 2.5 2 1.5 2 1.5	m/s	3D dec	e e e	am a	axial v 	12	y 14 16 Radial	5 18 (mm)
x 6d dov stream	1 2 3 4 5 5 6 6 7 7 8 9 9 9 100 111 122 133 144 15 16 17 18 14 15 16 17 18 19 10 10 11 12 13 14 15 5 6 6 7 7 8 8 9 9 10 10 11 11 12 13 5 5 6 6 7 7 8 8 9 9 10 10 11 11 11 11 11 11 11 11 11 11 11	1.24946 1.39456 1.49305 1.53434 1.59548 1.62508 1.62477 1.61637 1.57504 1.57504 1.57504 1.57504 1.57504 1.57504 1.3289 1.2437 1.12565 1.02907 0.8927 3.0.7171 UMEAN 1.3157 2.14609 3.1.5548 5.1.5777 5.1.5855	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 13 0.3561 13 0.3526 13 0.3526 13 0.36290 14 0.37280 14 0.37280 14 0.37280 15 0.3733 15 0.3733 15 0.3214 16 0.3756 15 0.3214 16 0.3756 15 0.3224 17 0.3756 10 0.3756 10 0.3756 10 0.3756 10 0.3756 10 0.3756 10 0.3756 10 0.3756 10 0.3756 10 0.3217 10 0.2127 18 0.2132 12 0.2136 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2146 16 0.2	7 27,45544 9 24,98043 2 23,50993 3 22,5251 9 22,3249 12 21,9763 12 21,9763 12 21,3763 15 22,7458 15 26,7765 15 28,7765 15 28,7765 15 28,2186 15 28,2185 16 31,4296 17 21,889 18 13,4296 19 13,542 10 14,7296 11 15,894 12 15,894 13 14,7296 13 13,5165 13 13,5165	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 2 -0.04305 5 -0.0259 2 -0.01333 7 -0.0259 2 -0.04305 4 -0.0259 4 -0.0310 5 -0.01333 7 -0.0310 63 -0.0216 5 -0.0216 55 -0.0255 21 -0.00518 29 -0.0618 44 -0.0250 55 -0.0255 59 -0.0618 44 -0.0250 55 -0.0255 52 -0.0255 52 -0.0255 52 -0.0255 52 -0.0255 55 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 <	6 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3037276 5 0.338343 5 0.338343 5 0.338243 6 0.338344 5 0.32455 1 0.32455 1 0.32455 9 0.285921 8 0.289033 44 0.287804 9 0.285921 1 WRMS 88 0.10608 90 0.285921 1 WRMS 88 0.10608 90 0.285921 1 WRMS 88 0.10608 90 0.21268 90 0.07871 49 0.17869 90 0.16289	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.90168 3 24.90168 3 24.90168 1 24.41863 3 24.90168 3 24.90168 3 24.90168 1 24.41863 1 24.41863 1 24.41863 1 34.908876 1 11.27361 1 10.27463	0.000025 0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007305 0.0021111 0.012747 0.006358 0.004007 0.005528 0.00384 0.0004943 0.0007151 0.000751 0.000648 0.000188 0.000183 0.000643 0.000845 0.00085	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1	m/s	3D doc 	e e e e e e e e e e e e e e e e e e e	arm a:	axial ve xial ve xial ve	12	y 14 16 Radial	5 18 (mm)
x 6d dov stream	1 2 3 4 5 6 6 7 7 8 9 0 9 0 111 122 133 144 15 16 17 18 112 13 14 15 16 17 18 112 13 14 15 16 19 10 10 112 13 14 15 15 16 16 10 112 112 112 112 112 112 112 112 112	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64753 1.62477 1.61633 1.5750 1.51714 1.41286 1.3289 1.24376 1.3289 1.24376 1.32548 5 1.0290 0.7171 UMEAN 1.3157 2 1.4609 3 1.50578 5 1.5777 5 1.5857 7 1.5857	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 16 0.35726 19 0.36206 19 0.36206 19 0.36296 10 0.3783 10 0.3783 10 0.3783 10 0.3783 10 0.3214 10 0.3214 10 0.3244 10 0.3244 10 0.3244 10 0.3257 10 0.2257 10 0.2258 10 0.2558 10 0.2558 10 0.2558 10 0.2558 10 0.2558 10 0.2558 10 0.2558 10 0.2558 10 0.2	7 27,45544 9 24,98043 2 23,50959 3 22,5251 9 22,3249 22 32,50959 3 22,5251 9 22,3249 22 32,49 6 22,3363 5 22,8350 9 23,7458 35 22,8350 9 23,7458 35 22,8350 9 23,7458 35 28,2165 55 28,2185 55 28,2185 55 28,2185 55 28,2185 55 28,2185 55 28,2185 56 31,4296 26 36,0035 56 31,4296 21 15,894 14,729 79 13,973 65 13,516 38 13,711 99 13,542 29 14,729 79 13,973 65 13,516 38 13,711 99 13,542 29 14,729 79 13,973 71 2,981 71 2,981 72 2,	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02597 2 -0.01333 7 -0.02597 2 -0.01384 4 -0.04305 5 -0.01384 4 -0.04005 5 -0.0310 54 -0.0216 55 -0.0133 67 -0.00671 64 -0.01053 10 -0.0216 55 -0.0216 56 -0.0255 57 -0.0618 44 -0.0256 57 -0.0255 59 -0.0214 50 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 <	0.023056 0.023056 0.056668 0.16751 0.325243 7 0.304988 9 0.314255 7 0.327251 6 0.335276 5 0.335276 6 0.335276 5 0.335276 6 0.335274 7 0.322852 1 0.32452 4 0.309703 9 0.285924 8 0.2867804 9 0.2867804 9 0.2867804 9 0.2867804 9 0.2867804 9 0.280932 1 WRMS 88 0.10608 80 0.10268 80 0.02396 91 0.17869 92 0.16249 93 0.16249	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 32.44054 24.90168 32.44054 32.23788 536.80275 WTURBU 4.8.02186 8.0817825 4.084762 4.0842313 1.541004 3.4.988876 1.1.127366 1.1.27366 1.1.27466 2.10.27467 2.10.2747 2.10.2747 2.10.2747 2.10.2747 2.10.2747 2.10.2747 2	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007302 0.007302 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.0004943 0.0007151 0.010675 1 uw 0.000064 0.000084 0.000084 0.000084 0.000084 0.0006751 0.00084 0.0006751 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006155 0.0006451 0.000655 0.000655 0.000655 0.000655 0.000655 0.000655 0.000655 0.00065 0.000655 0.000555 0.000555 0.000555 0.000555 0.000555 0.000555 0.000555 0.0005555 0.0005555 0.00055555 0.00055555 0.00055555555	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 1 5 1 5 1 5 1 5 1 5 1 5 1 5 1 5 5 1 5 1 5 1 0 5 5 1 1 5 1 1 5 5 1 1 5 5 5 1 5 5 5 5	m/s	3D dec	vnstre	am a	axial ve to the second se	12	y 14 10 Radial	5 18 (mm)
x 6d dov stream	1 2 3 4 5 6 6 7 7 8 9 9 9 0 111 122 133 144 155 6 6 7 7 8 9 9 9 0 0 111 122 133 144 152 133 144 152 133 14 14 14 15 15 16 16 10 11 12 13 14 15 15 16 16 17 17 18 18 19 10 11 11 12 13 14 15 15 16 16 10 11 11 12 11 11 11 11 11 11 11 11 11 11	1.24946 1.39456 1.49300 1.53434 1.59548 1.62506 1.64755 1.64755 1.61633 1.57504 1.51714 1.41286 1.24376 1.24376 1.24376 1.24377 1.2565 1.02907 0.8927 0.7171 UMEAN 1.31572 1.4609 3.1.50577 1.55556 1.6014 9.15855 1.6014 9.15855 1.6014 9.15855 1.6014 9.15855 1.6014 9.15855 1.6014 1.58556 1.58556 1.6014 1.58556 1.5856	9 0.34304 9 0.34836 9 0.34836 6 0.35101 13 0.3561 13 0.35226 29 0.36296 29 0.36296 13 0.37831 14 0.37400 14 0.37831 15 0.35091 74 0.30733 15 0.35091 74 0.30307 47 0.3234' 16 0.32756 13 0.2327 19 0.3756 13 0.2317 146 0.2172 178 0.2132 178 0.2132 178 0.2132 195 0.2132 195 0.2132 195 0.2132 195 0.2132 195 0.2132	7 27,45544 9 24,98043 9 24,98043 2 23,50993 3 22,5251 9 22,3249 12 21,9763 12 21,9763 15 22,8390 15 22,7765 15 28,7765 15 28,7765 15 28,7452 15 28,7452 15 28,7452 15 28,7452 26 31,4292 26 36,0935 54 46,9532 UTURB 13,973 65 13,516 38 13,711 199 13,973 65 13,963 13,981 13,9742 12 13,981 13,981 13,592	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02954 2 -0.04305 5 -0.02594 2 -0.01383 7 -0.0310 64 -0.0216 75 -0.01383 7 -0.0310 54 -0.0053 21 -0.00535 21 -0.00535 21 -0.00535 22 -0.0310 55 -0.0256 55 -0.0257 52 -0.03053 U W MEAN 59 -0.0366 59 -0.0325 50 -0.0326 52 -0.0326 53 -0.03214 56 -0.03224 56 -0.0124 56 -0.0124 56 -0.0125 54 -0.0024	5 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 6 0.335276 5 0.338343 5 0.338843 5 0.33892 6 0.32455 1 0.32452 4 0.302852 8 0.285926 8 0.285926 9 0.285926 8 0.10608 9 0.263920 1 0.328503 4 0.3028700 9 0.263920 1 0.12688 0.010608 0.01194 5 0.02396 0.02396 0.02396 0.07871 19 1 0.12689 2 0.16849 2 0.16750	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.4.41863 3.24.90168 3.2	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.009453 0.004943 0.004943 0.004943 0.004943 0.0004943 0.0007151 0.010675 1 1 1 1 2 3 0.000183 5 0.000183 5 0.000183 5 0.0006463 7 0.006571 4 0.006791 7 0.006571 7 0.006791	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 4	m/s	3D do	eventur good for good for good for good for for good for for good for for good for for for for for for for for for for	arm a:	Axial v	12	y 14 16 Radial	5 18 (mm)
x 6d dov stream	1 2 3 3 4 5 6 6 7 7 8 9 9 100 111 122 133 141 14 15 16 10 17 10 10 11 12 13 14 15 16 10 10 11 11 12 13 11 12 13 14 15 10 10 10 10 10 10 10 10 10 10 10 10 10	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64753 1.624753 1.61633 1.5750 1.51711 1.4128 1.3289 1.2437 1.1256 1.0290 0.8227 0.8227 1.24609 3.1.5057 1.51548 5.1.5777 5.1.5850 7.1.5850 7.1.5850 7.1.5853 8.1.6014 9.1.5833	9 0.34304 9 0.34836 9 0.34836 9 0.34836 14 0.35101 13 0.3561 13 0.35226 13 0.36290 13 0.36290 14 0.37400 14 0.37400 14 0.37400 14 0.37400 14 0.3783 15 0.3509 74 0.33070 147 0.3214 10 0.3214 10 0.3214 10 0.2317 186 0.2172 186 0.2172 198 0.2172 198 0.2132 199 0.2132 198 0.2132 198 0.2132 198 0.2132 198 0.2132 198 0.2132 198 0.2132 198 0.2132 <t< td=""><td>7 27,45544 9 24,98043 2 23,50993 3 22,5251 9 22,3249 12 21,9763 12 21,9763 12 21,9763 12 23,363 15 22,8390 15 22,7755 15 28,0462 20 31,4296 21 28,0462 22 29,383 26 31,4296 26 36,6033 51 28,5496 21 15,899 99 14,7293 79 13,973 38 13,711 99 13,542 112 13,981 138 13,5192</td><td>5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.01333 7 -0.0310 37 -0.0310 36 -0.04305 5 -0.01333 7 -0.0310 37 -0.0310 38 -0.01133 37 0.00878 34 0.0075 21 -0.00502 59 -0.06618 44 -0.0250 55 -0.0250 59 -0.0310 77 -0.06618 44 -0.0250 55 -0.0250 59 -0.0250 59 -0.0250 59 -0.02514 56 -0.0250 57 -0.0250 58 -0.02514 56 -0.0250 57 -0.02514</td><td>6 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 6 0.335276 5 0.338343 5 0.338843 5 0.33892 6 0.32452 1 0.32452 4 0.309703 9 0.285926 8 0.209732 9 0.228522 8 0.203926 9 0.2285926 8 0.203926 9 0.2285926 8 0.203926 9 0.2285926 8 0.203926 9 0.2285926 8 0.203926 9 0.228780 9 0.2283927 8 0.10608 9 0.203926 9 0.203926 9 0.17869 <!--</td--><td>1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.40583 24.41863 32.4,90168 32.4,90168 32.4,90168 32.4,90168 32.4,90168 32.4,90168 32.4,90168 32.4,90168 33.2,3786 33.2,3786 33.2,3786 33.4,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,90168 34.9,9016834.9,90168 34.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,90168 34.9,9016834.9,9016834.9,90168 34.9,9016835555555555555555555555555555</td><td>0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.006759 0.012111 0.012747 0.006358 0.009453 0.004007 0.005258 0.00384 0.000453 0.000453 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.00</td><td>2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2 5 2.5 2 1.5 2 5 1.5 1 5 2.5 3 2 5 1.5 1 0.5 5 2 5 1.5 5 2 5 1.5 5 7 0 -0.5 5 7 0 -0.5 5 7 0 -0.5 5 7 0 -0.5 5 7 0 -0.5 5 7 1 -0.5 5 7 1 -0.5 5 7 1 -0.5 5 7 1 -0.5 5 7 1 -0.5 5 7 1 -0.5 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x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 8 9 9 100 111 122 133 144 5 5 6 6 7 7 8 8 9 9 9 100 111 121 131 144 5 5 6 6 7 7 7 8 8 9 9 9 100 111 112 132 144 5 5 6 6 6 7 7 7 7 8 8 8 9 9 9 100 1111 112 132 144 5 5 6 6 6 7 7 7 7 8 8 8 9 9 100 1111 112 112 114 1111 112 112 112 112 1	1.24946 1.39456 1.49303 1.53434 1.59546 1.62508 1.62477 1.61633 1.57504 1.57504 1.57504 1.57504 1.57504 1.57504 1.24376 1.24376 1.24376 1.24376 1.24376 1.24376 1.24376 1.24376 1.24376 1.24376 1.25485 1.5777 1.58567 1.55485 1.55485 1.55485 1.55485 1.5548 1.55485 1.55485 1.5548 1.55588 1.55588 1.55	9 0.34304 9 0.34836 6 0.35101 13 0.3521 13 0.3521 13 0.3521 13 0.3521 13 0.3521 13 0.3629 13 0.3629 13 0.3629 14 0.37400 14 0.3783 10 0.3783 11 0.3783 12 0.3214 36 0.3214 36 0.3214 36 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2146 195 0.2235 166 0.2152 166 0.2165	7 27,45544 9 24,98043 2 23,5099 3 22,5251 9 22,3249 22 32,5099 3 22,5251 9 22,3249 22 3,249 22 3,249 22 3,249 22 3,249 23 7,458 24 5,277 5 28,2185 55 28,2185 55 28,2185 55 28,2185 55 28,2185 55 28,2185 56 31,4296 26 36,0035 54 46,9532 0 UTURB 51 28,549 21 15,899 91 4,729 79 13,973 65 13,516 38 13,711 38 13,711 38 13,711 38 13,512 39 14,522 31 3,542 31	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529 2 -0.04367 2 -0.04367 2 -0.04367 2 -0.04367 2 -0.04367 35 -0.0259 2 -0.01331 7 -0.03211 60 -0.04367 4 -0.0216 55 -0.0216 56 -0.01337 7 -0.06067 64 -0.01075 7 -0.0259 2 -0.0310 57 -0.0216 55 -0.0255 51 -0.0256 52 -0.0255 52 -0.0256 59 -0.0216 55 -0.0257 56 -0.0212 56 -0.0214 54 -0.0086 68 -0.0112 54 -0.0668 </td <td>6 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.303726 6 0.338343 5 0.338343 5 0.338574 5 0.338574 5 0.338574 5 0.338574 5 0.324552 1 0.324552 9 0.285926 8 0.289903 6 0.239903 7 0.0263920 8 0.10608 9 0.285926 9 0.285926 9 0.285926 8 0.10608 9 0.12688 9 0.12688 9 0.12688 9 0.12688 9 0.12689 9 0.12689 9 0.16780 9 0.16780 <t< td=""><td>1.845259 4.063463 11.21945 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-0,5 -1,5 -1,5 -1,5 -0,5 -1,5 -1,5 -1,5 -1,5 -1,5 -1,5 -1,5 -1</td><td>m/s</td><td>3D dec</td><td>e e e e e e e e e e e e e e e e e e e</td><td>am a</td><td>axial v 10</td><td>12</td><td>profile</td><td>5 18 (mm)</td></t<>	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 324.90168 325.40058 328.08762 432.23788 536.80275 W TURBU 1 8.062188 50.817825 40.842313 1 1.54100- 31.127366 1 11.27366 1 10.27467 2 10.5209- 4 10.5756 9 10.47567 9 10.47567	0.000025 0.000026 0.000084 -0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.00759 0.012111 0.012747 0.006358 0.004007 0.005258 0.00384 0.0004943 0.0007515 0.0007515 0.000751 0.000751 0.000757 0.000846 0.00086 0.00086 0.00086 0.00086 0.00086 0.00086 0.00086 0.0	2.5 2 1,5 1 0,5 0 -0,5 -1 -1.5 2 5 1,5 2 5 1,5 1 0,5 2,5 1 5 1,5 1 0,5 -1 -1.5 1 -1.5 1 0,5 -0,5 -1 -1,5 1 -0,5 -1,5 -1,5 -1,5 -1,5 -0,5 -0,5 -1,5 -1,5 -1,5 -0,5 -1,5 -1,5 -1,5 -1,5 -1,5 -1,5 -1,5 -1	m/s	3D dec	e e e e e e e e e e e e e e e e e e e	am a	axial v 10	12	profile	5 18 (mm)
x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 9 9 10 11 11 12 13 14 15 16 11 15 16 11 15 16 16 17 17 17 17 18 11 11 11 11 11 11 11 11 11 11 11 11	1.24946 1.39456 1.49303 1.53434 1.59544 1.62508 1.64753 1.62477 1.61633 1.5750 1.51714 1.41280 1.3289 1.24370 1.3157 2.14609 3.15057 4.1.5548 5.1.5777 5.1.5855 4.1.5548 5.1.5777 5.1.5855 8.1.6014 9.1.5685 9.1.5	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 16 0.35726 19 0.36206 19 0.36206 19 0.36296 10 0.3783 10 0.3783 10 0.3783 10 0.3783 10 0.3783 10 0.3214 10 0.3214 10 0.3244 10 0.3244 10 0.3244 10 0.3257 10 0.2252 10 0.2152 10 0.2	7 27,45544 9 24,98043 2 23,5099 3 22,5251 9 22,3249 22 32,5099 3 22,5251 9 22,3249 22 32,49 6 22,3363 5 22,8350 9 23,7458 35 22,8350 9 23,7458 35 22,8350 9 23,7458 35 22,8350 35 22,8350 36 24,8550 37 29,355 37 29,355 37 32,855 37 32,955 37 32,9555 37 32,9555 37 32,9555 37 32,9555 37 32,9555	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02937 7 -0.02597 2 -0.01333 7 -0.02597 2 -0.01384 4 -0.04305 5 -0.01384 4 -0.04305 5 -0.0310 54 -0.003211 57 -0.004305 51 -0.01384 40 0.0175 521 -0.0214 55 -0.0214 59 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0120 54 -0.0086 68 -0.0111 57 -0.0264	6 0.023056 4 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.327251 5 0.33832 6 0.33587 6 0.33587 1 0.32452 4 0.309703 9 0.285921 8 0.10608 8 0.10608 8 0.10608 9 0.28780 9 0.280932 1 0.2452 1 0.22872 1 WRMS 8 0.10608 9 0.280932 1 0.1268 32 0.16849 32 0.16849 32 0.16849 32 0.16744	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 32.440518 24.90168 32.440518 24.90168 32.440518 24.90168 32.440518 24.90168 32.440518 34.44051834.440518 34.440518 34.44051834.440518 34.44051834.440518 34.44051834.4	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.000494 0.000575 UW 0.000657 0.000657 0.000646 0.000675 0.000646 0.000675 0.000646 0.000675 0.00	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 1 5 1.5 1 5 1.5 1 5 1.5 1 5 1.5 1 -1.5 1 -1.5 1 -1.5 1 -1.5 -1.5	m/s	3D dc	winstre	am a:	axial v	12	ry 14 10 Radial	5 18 (mm)
x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 9 9 10 111 12 13 3 14 15 16 111 12 13 14 15 16 16 17 8 9 9 9 10 0 111 112 13 3 14 1 12 13 14 15 16 16 10 111 112 13 16 16 10 10 111 112 13 16 16 10 10 111 112 13 16 16 10 10 10 10 10 10 10 10 10 10 10 10 10	1.24946 1.39456 1.49303 1.53434 1.59548 1.62506 1.64752 1.61633 1.57504 1.51714 1.41286 1.32899 1.24376 1.32899 1.24376 1.32899 1.24376 1.32897 1.3266 1.02907 0.8927 0.7171 UMEAN 1.31577 1.55856 1.50577 1.58556 1.58557 1.58557 1.5855 1.58577 1.5585 1.5614 1.5588 1.5614 1.5588 1.5614 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888 1.55888	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 16 0.35726 29 0.36206 19 0.36296 19 0.36296 19 0.36296 19 0.36296 19 0.3733 30 0.3733 35 0.3733 35 0.3733 35 0.3733 35 0.3733 35 0.3733 35 0.3733 35 0.3733 35 0.3733 35 0.3736 53 0.3736 53 0.3276 53 0.232 98 0.2217 38 0.2172 78 0.2132 126 0.2132 126 0.2132 126 0.2132 126 0.2132 126 0.2132 126 0.2132 126 0.2132 126 0.2132 126 0.2135 126 0.2155 126 0.2155	7 27,45544 9 24,98043 2 23,50994 3 22,5251 9 22,3249 12 21,9763 12 21,9763 12 23,333 12 22,3333 15 22,8350 15 22,7775 15 26,7765 15 28,2777 15 28,2777 15 28,2777 15 28,2777 15 28,2777 15 28,3742 26 36,6035 27 28,0945 26 36,6035 27 38,0945 28 34,299 29 14,729 13,973 355 38 13,711 99 14,729 13,973 398 13,973 398 13,973 398 13,973 398 13,973 398	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.0133 7 -0.0259 2 -0.0138 4 -0.04011 5 -0.0138 4 -0.03211 7 -0.0216 34 -0.0216 35 -0.0113 36 -0.01310 37 0.00878 39 -0.0618 44 -0.0259 21 -0.0053 U W MEAN 59 -0.0254 92 -0.0302 77 -0.066 95 -0.0214 56 -0.0255 92 -0.0302 77 -0.066 95 -0.0214 56 -0.0255 57 -0.0053 54 -0.0086 <	5 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 7 0.327251 6 0.335276 5 0.33892 6 0.328527 1 0.32452 4 0.302952 8 0.328527 9 0.285927 8 0.289037 44 0.287800 9 0.283927 8 0.10608 9 0.283927 1 WRMS 88 0.10608 90 0.283927 1 0.12685 90 0.23927 10 0.12685 90 0.16849 92 0.16750 92 0.16750 932 0.16750 932 0.16744 48 0.17233	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 2.4.41863 3.24.90168 3.2	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.000455 0.000464 0.000635 0.0000646 0.000673 0.000646 0.000673 0.000646 0.000673 0.000646 0.000673 0.000675 0.000646 0.000790 0.00057 0.000470 0.00057 0.000470 0.00057 0.000470 0.00057 0.000675 0.00057 0	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 2 5 1.5 1 0.5 2 5 1.5 1 -1.5 1 0 -0.5 -1 -1.5 1 -1.5 -1 -1.5 -1 -0.5 -1 -1.5 -1.5	m/s	3D dec	winstre 6	eam a	axial v	12	ry 14 16 Radial	5 18 (mm)
x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 8 9 9 100 111 122 133 144 15 1 14 15 1 12 13 14 15 1 1 1 1 2 4 8 9 9 100 111 12 13 14 1 5 6 6 7 7 7 8 8 9 9 100 111 12 13 14 15 6 7 7 7 8 8 9 9 100 111 112 113 112 112 112 112 112 112 112	1.24946 1.39456 1.49303 1.53434 1.59548 1.62508 1.64753 1.624753 1.624753 1.61633 1.5750 1.51711 1.4128 1.3289 1.13256 1.0290 7.08927 3.0.7171 1.5548 1.0290 1.5657 1.5548 1.6014 9 1.5838 1.6014 9 1.5838 1.6014 9 1.5583 2.1.518 3.1.4844	9 0.34304 9 0.34836 6 0.35101 14 0.34631 13 0.3561 13 0.35226 13 0.35226 13 0.36290 14 0.34836 15 0.36290 16 0.37400 17 0.37400 14 0.37831 10 0.37331 10 0.3214 14 0.3214 15 0.3214 14 0.2172 16 0.2172 178 0.2172 166 0.2172 166 0.2132 166 0.2132 166 0.2132 166 0.2132 166 0.2132 166 0.2132 166 0.2132 166 0.2132 166 0.2132 166 0.2162 167 0.2162 <	7 27,4554 9 24,98043 2 23,5099 3 22,5251 9 22,3249 2 21,9763 5 22,3363 5 22,8390 9 23,7458 0 24,5727 15 26,7765 2 29,383 2 6,765 2 29,383 2 6,765 2 29,383 2 6,765 2 29,383 2 6,765 2 29,383 2 6,775 2 8,945 2 29,383 2 4,577 2 1,979 1 3,973 3 8,13,711 9 1 3,573 3 8,13,711 9 1 3,573 3 8,13,711 9 9 1 3,542 1 1 5,849 3 1 4,729 3 1	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.01333 7 -0.02594 2 -0.01383 4 -0.0310 54 -0.0310 57 -0.0310 54 -0.004878 50 -0.01363 57 -0.00532 21 -0.00532 21 -0.00555 59 -0.06618 44 -0.0250 55 -0.0310 59 -0.0618 44 -0.0250 55 -0.0255 52 -0.0302 54 -0.0302 55 -0.0256 54 -0.0302 54 -0.0307 54 -0.0066 57 -0.0053 58 -0.0111 59 -0.0053	6 0.023056 4 0.023056 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 7 0.335276 5 0.338343 5 0.338843 5 0.338844 5 0.32452 1 0.32452 4 0.302852 8 0.283926 9 0.285926 8 0.280933 44 0.287804 9 0.283926 88 0.10608 90 0.23936 91 0.263927 92 0.07871 932 0.16428 932 0.16429 932 0.16424 932 0.16424 932 0.16424 9352 0.16424 9352 0.16424 9352 0.16424 9352 0.1642	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.235093 2.24.41863 3.24.90168 3	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007305 0.012111 0.012747 0.006358 0.004007 0.00528 0.004007 0.00528 0.004007 0.00551 0.00183 0.000084 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.00084 0.000183 0.00084	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2 5 1.5 2 5 1.5 1 5 1.5 1 5 1.5 1 5 2.5 1.5 1 -1.5 1 0.5 5 -1 -1.5 1 0.5 5 -0 5 -0 5 -0 5 -0 5 -0 5 -0 5 -0	m/s	3D dec	winstree	arm a:	axial v 10	12	ry 14 16 Radial	5 18 (mm) 16 1/
x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 8 9 9 100 111 122 133 144 5 5 6 6 7 7 8 8 9 9 100 111 121 131 144 5 5 6 6 7 7 7 8 8 9 9 9 100 111 112 134 4 5 5 6 6 7 7 7 8 8 9 9 9 100 111 112 134 145 5 6 6 6 7 7 7 8 8 8 9 9 100 1111 112 134 145 5 6 6 6 7 7 7 8 8 8 9 9 100 1111 112 134 145 5 6 6 7 7 7 8 8 8 9 9 100 1111 112 134 145 144 15 144 111 112 114 111 112 114 111 112 114 111 111	1.24946 1.39456 1.49300 1.53434 1.59546 1.62508 1.62477 1.61633 1.57500 1.51714 1.41286 1.2256 1.02907 0.8227 0.7171 UMEAN 1.31572 1.55485 1.5057 1.55588 1.6014 9.1.5830 0.5673 1.5583 1.5583 1.5583 1.5673 1.55835 1.55835 1.55835 1.55835 1.55835 1.55835	9 0.34304 9 0.34836 6 0.35101 14 0.34836 15 0.35101 13 0.35216 13 0.35216 13 0.36290 14 0.37400 14 0.37831 10 0.37831 10 0.37831 10 0.37331 10 0.37331 10 0.3214 36 0.3214 36 0.23217 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 186 0.2172 195 0.2239 166 0.2162 195 0.2235 166 0.2162 198 0.2162	7 27,4554 9 24,9804; 2 23,5099; 3 22,5251 9 22,3249; 2 23,5099; 3 22,5251 9 22,3249; 2 21,9763 5 22,3363 5 22,8390 9 23,7458 04 24,5727 15 26,7765 73 28,0945 55 28,2185 55 28,2185 55 28,2185 55 28,2185 56 31,4296 26 36,0035 54 46,9532 46,9532 44,9523 54 46,9532 54 54 54 54 56 54 56 56 56 56 56 56 56 56 56 56 56 56 56	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05529 2 -0.04367 2 -0.04367 2 -0.04367 2 -0.04367 2 -0.04367 35 -0.0259 2 -0.01384 4 -0.04007 54 -0.04307 57 -0.0310 54 -0.01333 57 -0.0216 55 -0.0216 55 -0.0259 2 -0.0310 54 -0.0053 U W MEAN 59 -0.0216 55 -0.0255 52 -0.0255 52 -0.0255 52 -0.0212 54 -0.0212 55 -0.0214 56 -0.0123 54 -0.0086 68 -0.0115 55 -0.025 <td>5 0.023056 4 0.023056 5 0.16751 9 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325276 5 0.338323 5 0.338872 6 0.335874 5 0.322852 8 0.285921 8 0.285921 8 0.285921 8 0.285921 9 0.263921 9 0.263921 8 0.263921 9 0.263921 10 0.10608 56 0.02396 9 0.263921 10 0.16289 91 0.16289 92 0.16750 52 0.1714 91 0.16289 92 0.16750 <td>1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 324.90168</td><td>0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.004943 0.004943 0.004943 0.004943 0.0007151 0.010675 0.000848 0.0007451 0.0007451 0.0007451 0.0007451 0.0007453 0.000064 0.0007451 0.0006571 4.0007907 0.006571 4.0007907 0.006571 4.0007907 0.006571 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000857 0.00085</td><td>2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 7 0.5 4 7 0.5 4 7 0.5 1 5 1.5 1 -1.5 2.5 2 1.5 5 1.5 1 -0.5 -1 -1.5 -1.5</td><td>m/s</td><td>3D de</td><td>winstre</td><td>8</td><td>axial v 10 xial v xial v 10</td><td>12</td><td>ry 14 16 Radial</td><td>5 18 (mm)</td></td>	5 0.023056 4 0.023056 5 0.16751 9 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325243 7 0.325276 5 0.338323 5 0.338872 6 0.335874 5 0.322852 8 0.285921 8 0.285921 8 0.285921 8 0.285921 9 0.263921 9 0.263921 8 0.263921 9 0.263921 10 0.10608 56 0.02396 9 0.263921 10 0.16289 91 0.16289 92 0.16750 52 0.1714 91 0.16289 92 0.16750 <td>1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 324.90168</td> <td>0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.004943 0.004943 0.004943 0.004943 0.0007151 0.010675 0.000848 0.0007451 0.0007451 0.0007451 0.0007451 0.0007453 0.000064 0.0007451 0.0006571 4.0007907 0.006571 4.0007907 0.006571 4.0007907 0.006571 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000857 0.00085</td> <td>2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 7 0.5 4 7 0.5 4 7 0.5 1 5 1.5 1 -1.5 2.5 2 1.5 5 1.5 1 -0.5 -1 -1.5 -1.5</td> <td>m/s</td> <td>3D de</td> <td>winstre</td> <td>8</td> <td>axial v 10 xial v xial v 10</td> <td>12</td> <td>ry 14 16 Radial</td> <td>5 18 (mm)</td>	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 324.90168	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.004943 0.004943 0.004943 0.004943 0.0007151 0.010675 0.000848 0.0007451 0.0007451 0.0007451 0.0007451 0.0007453 0.000064 0.0007451 0.0006571 4.0007907 0.006571 4.0007907 0.006571 4.0007907 0.006571 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000846 0.000657 1.000857 0.00085	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 7 0.5 4 7 0.5 4 7 0.5 1 5 1.5 1 -1.5 2.5 2 1.5 5 1.5 1 -0.5 -1 -1.5 -1.5	m/s	3D de	winstre	8	axial v 10 xial v xial v 10	12	ry 14 16 Radial	5 18 (mm)
x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 9 10 11 11 12 14 15 16 11 12 13 14 15 16 11 12 13 14 15 16 16 11 12 13 14 15 16 16 10 11 11 12 13 14 15 16 10 11 11 12 13 14 15 16 10 10 11 11 11 12 13 14 15 16 10 10 11 11 11 11 11 11 11 11 11 11 11	1.24946 1.39456 1.49303 1.53434 1.59544 1.62508 1.64757 1.624757 1.61633 1.57500 1.51714 1.41280 1.3289 1.24370 1.3157 2.1.4609 3.1.5057 4.1.5548 5.1.5777 5.1.5548 5.1.5777 5.1.5850 7.1.5850 7.1.5851 9.1.5833 0.1.5671 1.5583 2.1.51843 3.1.4430 5.1.391	9 0.34304 9 0.34836 6 0.35101 14 0.34561 13 0.3561 14 0.34636 13 0.3561 14 0.34636 13 0.3561 14 0.34636 13 0.36296 14 0.37400 14 0.37400 14 0.37337 15 0.37337 16 0.37337 17 0.3214 13 0.3257 147 0.3367 147 0.3234 15 0.3214 16 0.2132 16 0.2172 186 0.2172 186 0.2142 195 0.2233 196 0.2132 196 0.2132 196 0.2146 197 0.2166 198 0.2166 199 0.2165 <tr< td=""><td>7 27,45544 9 24,98043 2 23,50959 3 22,5251 9 22,3249 22 33,50959 3 22,5251 9 22,3249 22 32,50959 3 22,5251 9 22,3249 22 3,7458 35 22,8350 35 22,8350 30 23,7458 35 22,8350 30 23,7458 35 22,8350 35 22,8350 36 23,7458 36 24,572 37 24,572 37 3,575 37 3,575 37 3,575 37 3,575 37 4,575 37 4,575 37 4,575 38 1,3750 39 1,3750 39 1,3750 39 1,3750 39 1,3750 30 1,4750 30 1,4750</td><td>5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02597 2 -0.01333 7 -0.02597 2 -0.01388 4 -0.04305 5 -0.01388 4 -0.04305 5 -0.0310 54 -0.04000 55 -0.0216 54 -0.0053 U W MEAN 59 -0.0214 56 -0.0254 56 -0.0255 57 -0.06618 44 -0.0255 50 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 57 -0.0066 57 -0.0053 57 -0.0054 58 -0.0120 54 -0.0054</td><td>6 0.023056 4 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.325243 7 0.325243 7 0.325243 7 0.327251 5 0.338326 6 0.335874 5 0.322852 4 0.309703 9 0.285921 8 0.10608 9 0.285921 8 0.10608 9 0.280932 1 0.280932 1 0.12689 2 0.070104 9 0.263921 1 0.16289 2 0.16740 91 0.16289 92 0.16740 932 0.16849 932 0.16849 932 0.16849 932 0.16750 </td></tr<> <td>1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 32.40058 24.41863 24.90168 32.40058 32.40058 32.40058 32.40058 33.24,90168 32.40058 33.24,90168 32.40058 33.24,90168 32.23788 32.4,901683</td> <td>0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007302 0.007305 0.004253 0.004943 0.004943 0.004943 0.004943 0.004943 0.0004943 0.0004943 0.0007151 0.010875 1.000 0.0006371 0.0006375 0.0006575 0.0006575 0.0006575 0.0006575 0.</td> <td>2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 2 1.5 1 0.5 2 1.5 1 0.5 2 5 1.5 1 -1.5 1 -1.5 2 5 1.5 -1 -1.5 5 2 5 -1 -1.5 5 -1.5 -1.</td> <td>m/s</td> <td>3D dc</td> <td>winstre</td> <td>am a</td> <td>axial v</td> <td>12</td> <td>profile</td> <td>5 18 (mm)</td>	7 27,45544 9 24,98043 2 23,50959 3 22,5251 9 22,3249 22 33,50959 3 22,5251 9 22,3249 22 32,50959 3 22,5251 9 22,3249 22 3,7458 35 22,8350 35 22,8350 30 23,7458 35 22,8350 30 23,7458 35 22,8350 35 22,8350 36 23,7458 36 24,572 37 24,572 37 3,575 37 3,575 37 3,575 37 3,575 37 4,575 37 4,575 37 4,575 38 1,3750 39 1,3750 39 1,3750 39 1,3750 39 1,3750 30 1,4750 30 1,4750	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.02597 2 -0.01333 7 -0.02597 2 -0.01388 4 -0.04305 5 -0.01388 4 -0.04305 5 -0.0310 54 -0.04000 55 -0.0216 54 -0.0053 U W MEAN 59 -0.0214 56 -0.0254 56 -0.0255 57 -0.06618 44 -0.0255 50 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 56 -0.0214 57 -0.0066 57 -0.0053 57 -0.0054 58 -0.0120 54 -0.0054	6 0.023056 4 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.325243 7 0.325243 7 0.325243 7 0.327251 5 0.338326 6 0.335874 5 0.322852 4 0.309703 9 0.285921 8 0.10608 9 0.285921 8 0.10608 9 0.280932 1 0.280932 1 0.12689 2 0.070104 9 0.263921 1 0.16289 2 0.16740 91 0.16289 92 0.16740 932 0.16849 932 0.16849 932 0.16849 932 0.16750	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.85093 24.41863 24.90168 32.40058 24.41863 24.90168 32.40058 32.40058 32.40058 32.40058 33.24,90168 32.40058 33.24,90168 32.40058 33.24,90168 32.23788 32.4,901683	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007302 0.007305 0.004253 0.004943 0.004943 0.004943 0.004943 0.004943 0.0004943 0.0004943 0.0007151 0.010875 1.000 0.0006371 0.0006375 0.0006575 0.0006575 0.0006575 0.0006575 0.	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 2 1.5 1 0.5 2 1.5 1 0.5 2 5 1.5 1 -1.5 1 -1.5 2 5 1.5 -1 -1.5 5 2 5 -1 -1.5 5 -1.5 -1.	m/s	3D dc	winstre	am a	axial v	12	profile	5 18 (mm)
x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 9 9 10 111 12 13 3 14 15 16 11 11 12 13 3 14 15 16 16 17 8 9 9 9 10 0 111 112 13 3 14 15 16 16 10 111 112 13 13 14 15 16 16 10 111 112 13 13 14 15 16 16 10 111 112 13 13 14 111 112 13 14 111 112 13 14 111 112 13 14 111 112 113 114 111 112 113 111 111 112 113 111 111 112 113 111 111	1.24946 1.39456 1.49303 1.53434 1.59548 1.62506 1.64755 1.62475 1.61633 1.57504 1.51714 1.4128 1.3266 1.0290 1.24376 1.12566 1.0290 1.24376 1.1256 1.0290 1.24376 1.1256 1.0290 1.24376 1.1256 1.0290 1.24376 1.5585 1.6014 1.3157 2.1.5685 1.6014 1.5585 2.1.5183 3.1.4843 4.1430 5.1.391 6.1.3391	9 0.34304 9 0.34836 6 0.35101 14 0.3451 13 0.3521 13 0.3522 13 0.3522 13 0.3629 13 0.3629 14 0.34836 15 0.3629 16 0.37400 14 0.37837 15 0.35091 74 0.33070 47 0.3234' 51 0.3256 53 0.2329 98 0.2217 78 0.2132 126 0.2172 78 0.2132 136 0.2142 195 0.2232 196 0.2173 168 0.2172 78 0.2132 195 0.2235 196 0.2162 195 0.2235 196 0.2162 197 0.2162	7 27,45544 9 24,98043 2 23,50994 3 22,5251 9 22,3239 12 21,9763 12 21,9763 12 23,333 15 22,3233 15 22,571 15 22,37458 14 24,5727 15 26,77655 26 31,4296 26 36,6033 51 28,5496 21 15,899 99 14,7294 13 971 13 973 38 13<711	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04365 5 -0.0259 2 -0.0133 7 -0.0259 2 -0.0138 4 -0.04001 5 -0.0138 4 -0.0216 55 -0.0113 57 -0.0216 54 -0.0053 21 -0.0053 21 -0.0055 22 -0.0130 59 -0.0618 44 -0.0255 92 -0.03053 U W MEAN 59 -0.0254 92 -0.0305 92 -0.0302 59 -0.0254 92 -0.0305 51 -0.0254 52 -0.0305 54 -0.0026 55 -0.0366 68 -0.0111	0.023056 0.023056 0.056668 0.304988 0.314255 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.335276 0.322852 0.322852 0.322852 0.328926 0.2285927 80.010608 0.2285927 80.010608 0.2285927 80.010608 0.228780 90.2283921 WRMS 88.010608 0.01194 0.10608 0.02396 0.16849 0.16849 0.16750 52.016744 0.16849 22.016744 0.16849 31.016847 32.016849 31.016847 31.016847 31.016847 <	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.93215 21.51811 22.13855 22.4.4863 32.4.4863 32.4.90168 33.4.90168 34.980876 1 1.541004 3 1.980876 1 1.05209 4 1.05756 9 10.47567 1 1.9813 <td>0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.0004943 0.0007151 0.00183 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.000735 0.000846 0.0008735 0.0008476 0.0008735 0.0008755 0.000</td> <td>2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 2 1.5 1 0.5 2 1.5 1 0.5 2 5 1.5 1 -1.5 1 -1.5 2 5 1.5 1 -0.5 5 -1 -1.5 5 2 5 2 5 1.5 -1 -1.5 5 5 2 5 5 1 -0.5 5 -1 -1.5 5 5 2 5 1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 -1.5 -1.</td> <td>m/s</td> <td>3D dc</td> <td>winstre 6 vinstre 6</td> <td>eam a</td> <td>axial v</td> <td>12</td> <td>ry 14 16 Radial</td> <td>5 18 (mm)</td>	0.000025 0.000026 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007306 0.006759 0.012111 0.012747 0.006358 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.004943 0.0004943 0.0007151 0.00183 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.0000846 0.000735 0.000846 0.0008735 0.0008476 0.0008735 0.0008755 0.000	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 2 1.5 2 1.5 1 0.5 2 1.5 1 0.5 2 1.5 1 0.5 2 5 1.5 1 -1.5 1 -1.5 2 5 1.5 1 -0.5 5 -1 -1.5 5 2 5 2 5 1.5 -1 -1.5 5 5 2 5 5 1 -0.5 5 -1 -1.5 5 5 2 5 1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 5 -1 -1.5 5 -1.5 -1.	m/s	3D dc	winstre 6 vinstre 6	eam a	axial v	12	ry 14 16 Radial	5 18 (mm)
x 6d dov stream	1 2 3 4 4 5 6 6 7 7 8 8 9 9 100 111 12 133 14 15 14 15 13 14 15 13 14 15 14 15 14 15 14 15 16 16 10 11 11 12 13 14 15 16 10 11 11 12 13 14 15 10 10 11 11 11 11 11 11 11 11 11 11 11	1.24946 1.39456 1.39456 1.49303 1.53434 1.59544 1.62508 1.62473 1.61633 1.5750 1.5171 1.4128 1.3289 1.2437 1.4128 1.3289 1.2437 1.13157 1.5756 1.5757 1.5548 1.6014 9 1.5548 1.6014 9 1.5833 0 1.5673 1.5558 1.6014 9 1.5833 0 1.5673 1.5583 1.444 4 1.4300 5 1.391 6 1.3191 7 1.191	9 0.34304 9 0.34836 9 0.34836 9 0.34836 13 0.35101 13 0.3521 13 0.35226 13 0.36290 13 0.36290 14 0.34836 15 0.36290 16 0.37400 14 0.37837 10 0.37337 10 0.37337 10 0.32147 14 0.30716 15 0.32132 16 0.2172 178 0.2172 186 0.2172 198 0.2172 198 0.2132 196 0.2132 196 0.2132 196 0.2132 196 0.2132 196 0.2132 196 0.2132 197 0.2132 198 0.2132 199 0.2132	7 27,45544 9 24,98043 9 24,98043 2 23,50993 3 22,5211 9 22,32393 12 21,9763 12 21,9763 15 22,3233 15 22,37458 16 24,5727 15 28,0945 15 28,0945 15 28,042 26 31,4296 26 36,0035 21 15,899 99 14,7297 13,9733 26 14,7297 13,9733 65 13,5167 38 13,711 99 13,542 112 13,981 138 13,780 924 13,916 933 15,221 9342 14,529 935 15,237 936 14,529 937 15,221 938 15,221 939 15,251 932 15,237	5 -0.03236 2 -0.07054 9 -0.06516 1 -0.05522 2 -0.04305 5 -0.0259 2 -0.0133 7 -0.0259 2 -0.0138 4 -0.0310 5 -0.0138 4 -0.0310 54 -0.0138 4 -0.0310 54 -0.0138 4 -0.0310 54 -0.0138 4 -0.0216 35 -0.0138 4 -0.0256 5 -0.0138 4 -0.0256 55 -0.0256 57 -0.0302 92 -0.0302 92 -0.0302 92 -0.0302 54 -0.0066 68 -0.0112 54 -0.0065 57 -0.035 52 -0.035	5 0.023056 4 0.056668 5 0.16751 9 0.325243 7 0.304988 9 0.314255 7 0.3035276 7 0.335276 5 0.338343 5 0.338843 5 0.338844 5 0.32452 1 0.32452 4 0.302852 8 0.283926 9 0.285926 8 0.280933 44 0.287804 9 0.285926 88 0.10608 9 0.283927 9 0.283927 9 0.283927 9 0.283927 9 0.283927 9 0.283927 9 0.283927 9 0.283927 9 0.283927 9 0.17869 91 0.16424 9 0.16424	1.845259 4.063463 11.21945 21.19753 19.11568 19.33777 19.86316 20.63579 20.3215 21.19753 20.33215 21.51811 22.385093 24.90168 32.4,0168 33.2,23788 33.4,08876 11.2,7361 11.0,5246 311.22746 311.2291 911.40554 311.2891 911.801 11.801	0.000026 0.000028 0.000084 0.00101 0.003914 0.00459 0.007302 0.007302 0.007302 0.007305 0.004259 0.0042747 0.006358 0.004407 0.005288 0.00384 0.004943 0.007951 0.007951 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.000183 0.000084 0.00084	2.5 2 1.5 1 0.5 0 -0.5 -1 -1.5 2.5 1.5 2 5 1.5 1 0.5 4 0.5 1.5 1 0.5 2 1.5 1 -1.5 1 0 -0.5 -1 -1.5 2 5 1.5 1 -1.5 5 2 5 1.5 1 -1.5 5 2 5 1.5 5 2 5 5 1 5 2 5 5 1 5 5 5 5 5 5 5 5 5	m/s	3D do	wnstre	arm a:	axial ve i 10 xial ve i 10	12	ry 14 16 Radial	5 18 (mm) 16 1/



VELOCITY RAW DATA - 1mm ECCENTRIC BALL OCCLUDER

X	ΥU	IMEAN	URMS L	J TURBU V	VMEAN W	RMS W	/ TURBU u	w			_				
1D dow	1	-0.82398	0.397122	48 19538	-0.04742 0	033315	043176	-0.00036							
stream	2	-0.74086	0.408001	55 07121	-0 06945 0	103103	13,9167	-0.00162	2.5 T	en la					<u>∿</u>
	3	-0.82794	0.366205	44,23071	-0.01523 0	139668	16.86928	0.004895	2 +	1103				025	-
	4	-0.25011	0.472618	188,9645	-0.05515	0,1573 0	175 1868	0.000722	1.5						B-B-B
	c e	-0.29077	0.510594	336 6016	-0.0142 0	0 57492	379.0074	-0.01194							
	7	0.081406	0 571735	702.3272	-0.06716 0	661735	812.8848	-0.05971	. 1			1		-	B-B-B
	8	0.242712	0.592641	244,1746	-0.09593 0	708453	291.89	-0.07932	0.5	5		-	11 II	-	h
	9	0.348465	0.604653	173 5193	-0.12817 0	702134	201.4938	-0.08978	0			A.		-	-
	#	0,502599	0.615926	122.5483	-0 19172 (697708	138.8201	-0.1048	-0.5 0		6	10	10	12	14 16 18
	#	0,689385	0.644824	93,53606	-0 22454 (674322	97.81506	-0.11259		and)	p				Radial (mm)
	#	0,866897	0.677926	78,20143	-0 27943 (678838	78 306/3	0.1305	-1 1	8-8-8					
	#	1.0035	0,697523	69,50904	-0.25942 (0 624561	61.137.14	-0.10000	-1.5 🕹						
	#	0.993306	0.090229	70 29343 81 57129	-0.19304 (593675	68.55851	-0.17012	_			_			
	#	0.003333	0.675328	91.10665	0.004531	0 541877	73.10304	-0.15061							
	#	0.864087	0.66426	76.87426	-0.01206	0.523798	60.61865	-0.13316							
	#	0.850164	0.642555	75.58015	-0.0766	0.468381	55.09303	-0.11454							
x	Y	U MEAN	URMS	U TURBU	W MEAN V	VRMS	W TURBU	uw			_	_	_		
2D dow	/ 1	0.466349	0,45335	97.21251	-0.03032	0 017984	3.856365	0.000446			2D dow	vnstrea	m veloc	ity pro	file
stream	2	0.712323	0,501087	70.34552	-0 04556	0.040615	5.701742	0.000164	2.5 T	mva.		• 1.7.5			
	3	0.806851	0.514204	63,7297	-0.099/4	0.358848	44.4/312	0.012925	2 +		-	-	8-8-1	-0-0	1-1-a
	4	1.00509	0.518505	51.58/94	-0.07440	0.450842	36 86239	0.003085	1.5		H. H.	-	0-0-1		
	2	1.223041	0.5457.34	44 02 107	-0.05634	0 491735	37 64402	0.003859		Jan M	100	r _	B-0-1		- B-B-B-B
	7	1 467529	0.564531	38.46812	-0.06984	0.525978	35.84105	-0.00353	11	W B-W	1	-			B-B-B
	, 8	1.535287	0.555587	36.18784	-0.05183	0.535388	34.87216	-0.00624	0.5		R				
	9	1.568305	0.535738	34,16031	-0.04863	0.521931	33.27994	-0.00767	0	-			1	-1	
	#	1.564722	0.507599	32.44023	-0.00923	0.497994	31.82639	-0.00474		2	4 6	5 8	10	12	14 16 18
	#	1.544442	0.488548	31.63269	-0 0237	0.478601	30,98859	-0.00669	-0.5 T	-					Radiai (mm)
	#	1.510054	0.476559	31.55908	-0.01064	0.443986	29.402	-0.00899	-1 +						
	#	1.498165	0.476228	31.7874	-0.03038	0.433398	28.92856	-0.01955	-1.5						
	#	1.437781	0.470378	32,71557	-0.03476	0.424861	29.54977	-0.03377							
	#	1.343158	0.497211	37.01808	-0.02744	0.407778	30.35969	-0.03796-							
	#	1.267054	0.502529	39.66121	-0.00972	0.398624	31.46072	-0.05124							
	#	1.111872	2 0.48509	43.62825	-0.0219	0.302100	34:37324	-0.04793							
	#	0.85355	0.458273	23.09993	-0 03325	0.342415	40.11030	-0.00-122							
			II DUC	110011	WHEAN	WDMS	W TUPBU	ITW							
X	Y	U MEAN	URMS	U TURBU	W MEAN 1	W RMS 0.026483	2 376538	uw 0.000463			3D do	wnstre	am velo	city or	ofile
X 3D dor stream	Y w 1 1 2	U MEAN 1,11435 1,2349	URMS 0.395545 3.0.406375	U TURBU 5 35,4955 5 32,9051	-0 03893 -0 0376	W RMS 0 026483 0 024275	W TURBU 2.376538 1.96562	0.000463 0.000445	2.5	e/m	3D do	wnstre	am velo	city pr	ofile
X 3D do stream	¥ w 1 ت 2	U MEAN 1.11435 1.2349 1.36935	URMS 1 0.395545 3 0.406375 3 0.418617	U TURBU 5 35.4955 5 32.9051 7 30.5704	W MEAN -0.03893 -0.0376 -0.08328	W RMS 0.026483 0.024275 0.100589	W TURBU 2.376538 1.96562 7.345745	uw 0.000463 0.000445 0.001413	2.5	- m/s	3D do	wnstre	am velo	city pr	ofile
X 3D doi stream	Y w 1 1 2 3 4	U MEAN 1.11433 1.2349 1.36935 1.42576	URMS 0.395545 0.406375 0.418617 5 0.418456	U TURBU 35,4955 32,9051 30,5704 30,5704 329,13918	W MEAN -0 03893 -0 0376 -0 08328 -0 04011	W RMS 0 026483 0 024275 0 100589 0 343183	W TURBU 2.376538 1.96562 7.345745 24,07008	uw 0.000463 0.000445 0.001413 0.013304	2.5 2	- m/s	3D do	wnstre	am velo 	icity pr	ofile
X 3D do stream	Y 1 2 4 5	U MEAN 1,11435 1.2349 1.36935 1.42576 1.5286	URMS 0.395545 0.406375 0.418617 0.415456 0.423366	U TURBU 35 4955 32.9051 30.5704 29.13918 27 69489	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503	W RMS 0 026483 0 024275 0 100589 0 343183 0 34981	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313	uw 0.000463 0.000445 0.001413 0.013304 0.015686	2.5 2 1.5	- m/s	3D do	wnstre	am velo 	icity pr	ofile
X 3D da stream	Y 1 2 4 5 6	U MEAN 1,11435 1,2349 1,36935 1,42576 1,42576 1,5286 1,5286 1,62413	U RMS 1 0.395545 3 0.406375 3 0.418617 5 0.415456 8 0.423366 5 0.441281	U TURBU 5 35,4955 5 32.9051 7 30,5704 5 29.13918 5 27,69489 1 27,17024	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247	W RMS 0 026483 0 024275 0 100589 0 343183 0 34981 0 366759	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181	0.000463 0.000445 0.001413 0.013304 0.015686 0.025447	2.5 2 1.5 1 -	- m/s	3D do	wnstre 8-9-0 0-0-0 8-9-9	am velo 	icity pr	
X 3D do stream	Y 1 2 4 5 7	U MEAN 1.11435 1.2349 1.36935 1.42576 1.42576 1.5286 1.5286 1.62413 1.70326	U RMS 1 0.395545 3 0.406375 3 0.418617 5 0.415456 8 0.423366 5 0.441281 3 0.44848	U TURBU 5 35 4955 5 32.9051 7 30 5704 5 29.13918 5 27 69489 1 27.17024 3 26 33066	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272	W RMS 0 026483 0 024275 0 100589 0 343183 0 34981 0 366759 0 38457	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843	0.000463 0.000445 0.001413 0.013304 0.015686 0.025447 0.025301	2.5 2 1.5 1	m/s	3D do	wnstre B-B-N D-D-D B-B-N	am velo 	City pr	
X 3D do stream	Y 1 1 2 4 5 7 8	U MEAN 1.11435 1.2349 1.36935 1.42576 1.5286 1.62413 1.70326 1.70326 1.74276	U RMS 1 0.395545 3 0.406375 3 0.418617 5 0.415456 3 0.423366 5 0.441281 3 0.44848 9 0.445701	U TURBU 5 35,4955 5 32.9051 7 30,5704 5 29,13918 5 27,69489 1 27,17024 3 26,33066 1 25,57428	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094	W RMS 0 026483 0 024275 0 100589 0 343183 0 34981 0 366759 0 38457 0 389591	W TURBU 2.376538 1.96562 7.345745 24.07008 22.68313 22.58181 22.57843 22.3547	UW 0.000463 0.000445 0.001413 0.013304 0.015686 0.025447 0.025301 0.020307	2.5 2 1.5 1 0.5	m/s	3D do	wnstre 8-8-8 0-0-0 8-8-8	am velo 	icity pr	
X 3D do stream	Y 1 1 2 4 5 7 8	U MEAN 1.11435 1.2349 1.36935 1.42576 1.5286 1.5286 1.62413 1.70326 1.74276 1.76909	U RMS 1 0.395545 3 0.406375 3 0.416617 5 0.415456 8 0.423366 5 0.441281 3 0.44848 9 0.448701 1 0.432701	U TURBU 5 35,4955 5 32,9051 7 30,5704 5 27,69489 1 27,17024 3 26,33066 1 25,57428 1 24,45892 2 4,45892	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.00496	W RMS 0 026483 0 024275 0 100589 0 343183 0 34981 0 366759 0 38457 0 389591 0 393376	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.3545	UW 0.000463 0.000445 0.001413 0.013304 0.015686 0.025447 0.025301 0.020307 0.025627	2.5 2 1.5 1 0.5 0.5	e/m e/m e/m e/m e/m e/m e/m e/m e/m e/m	3D do	wnstre 8-9-8 0-0-0 8-9-8	am velo 	icity pr	
X 3D do stream	Y 1 1 2 4 5 6 7 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8	U MEAN 1.11433 1.2349 1.36935 1.42576 1.5286 1.5286 1.62413 1.70326 1.70326 1.74275 1.76909 1.74215	URMS 0.395545 0.406375 0.418617 5.0.412456 0.423366 0.44281 0.44281 0.444848 9.0.445701 1.0.432701 4.0.443632 0.443632	U TURBU 5 35,4955 5 32,9051 7 30,5704 5 29,13918 5 27,69489 1 27,17024 8 26,33066 1 25,57428 1 24,45892 9 25,46405 4 25,70261	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.00496 0.0020144	W RMS 0.026483 0.024275 0.100589 0.343183 0.34981 0.366759 0.38457 0.389591 0.393376 0.393376 0.396888	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.23605 22.78148 22.85323	UW 0.000463 0.000445 0.001413 0.013304 0.015686 0.025447 0.025301 0.020307 0.025627 0.025107	2.5 2 1.5 1 0.5 0 -0.5	m/s	3D do	wnstre 	am velo 	icity pr	ofile
X 3D do stream	Y 1 1 2 4 5 6 7 8 8 7 8 8 7 8 8 7 8 8 7 8 8 8 7 8 8 8 8 7 8 8 8 7 8 8 8 7 8 8 8 7 8 8 8 7 8 8 8 7 8 8 7 8 8 7 8 7 8 7 8 8 7 8 8 7 8 8 7 8 7 8 7 8 7 8 7 8 7 8 7 8 7 8 7 8 8 7 8 8 7 8 8 7 8 8 7 8 8 7 8 8 7 8 8 7 8 8 8 7 8 8 8 8 8 8 8 8 8 8 8 8 8 8 9 8 8 8 7 8 8 8 8	U MEAN 1.11435 1.2349 1.36935 1.42576 1.5286 1.5286 1.62413 1.70326 1.74276 1.76909 1.74215 1.09340 1.65290	URMS 0.395545 0.406375 0.418617 5.0.415456 0.41281 0.441281 0.44848 9.0.445701 1.0.432701 4.0.443636 6.0.432764 0.443564 0.443564 0.0435764	U TURBU 5 35,4955 5 32,9051 7 30,5704 5 27,69489 1 27,17024 3 26,33066 1 25,57428 1 24,45892 9 25,46405 4 25,70251 9 25,81437	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.00496 0.00496 0.00496 0.00459	W RMS 0.026483 0.024275 0.100589 0.343183 0.34981 0.366759 0.38457 0.389591 0.393376 0.393376 0.387457 0.387457	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.23605 22.78148 22.85332 21.85985	0.000463 0.000445 0.001413 0.01304 0.015866 0.025447 0.025301 0.025301 0.025627 0.025627 0.021107 0.016034 0.007665	2.5 2 1.5 1 0.5 - 0 - -0.5	m/s	3D do	wnstre 	am velo 	Deity pr	ofile
X 3D da strean	Y 12 1 34 56 7 8 8 #####	U MEAN 1.11435 1.2349 1.36935 1.42576 1.5286 1.5286 1.62413 1.70326 1.74276 1.76909 1.74215 1.66290 1.56290 1.56290	URMS 1 0.395545 3 0.406375 3 0.418617 5 0.415456 3 0.423366 5 0.441281 3 0.442306 9 0.4445701 1 0.432701 4 0.443635 8 0.435764 6 0.429265 4 0.429465	U TURBU 5 35.4955 32.9051 7 30.5704 5 29.13918 6 27.69489 1 27.17024 8 26.33066 1 25.57428 1 24.45892 9 25.46465 4 25.70251 9 25.81437 9 26.65036	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.015024 -0.015024 -0.015024 -0.01598 -0.01988	W RMS 0.026483 0.024275 0.100589 0.343183 0.34981 0.36759 0.38457 0.389591 0.393376 0.396388 0.363509 0.353943	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.23605 22.78148 22.85332 21.85988 22.43376	UW 0.000463 0.000445 0.001413 0.01304 0.015886 0.025447 0.025301 0.025301 0.025627 0.025627 0.021107 0.016034 0.00565 0.00505	2.5 2 1.5 1 - 0.5 - 0.5 - 1 -	m/s	3D do	wnstre 	am velo 	icity pr	ofile
X 3D da stream	Y 12 4 5 6 7 8 8 # # # # # #	U MEAN 1.11433 1.2349 1.36935 1.42576 1.5286 1.5286 1.62413 1.70326 1.74276 1.76909 1.74275 1.09340 1.662900 1.57772 1.52054	URMS 1 0.395545 3 0.406375 3 0.416517 5 0.415456 3 0.423366 5 0.441281 3 0.44281 9 0.4445701 1 0.432701 4 0.443635 8 0.435764 6 0.429265 4 0.429453 9 0.421733 9 0.421733	U TURBU 5 35.4955 32.9051 7 30.5704 5 29.13918 5 27.69489 1 27.17024 8 26.33066 1 25.57428 1 24.45892 9 25.46495 4 25.70251 9 25.81437 9 26.65036 5 27.7357	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.015024 -0.015024 -0.015024 -0.015024 -0.015024 -0.01098 -0.01098 -0.01098	W RMS 0 026483 0 024275 0 100589 0 343183 0 343183 0 345759 0 3865759 0 3865759 0 389591 0 393376 0 393376 0 396888 0 387457 0 363509 0 353943 0 352943	W TURBU 2.376538 1.96562 24.07008 22.88313 22.58181 22.57843 22.3547 22.23605 22.78148 22.85332 21.85988 22.43376 21.86133	UW 0.000463 0.000445 0.001413 0.01304 0.015686 0.025447 0.025301 0.025307 0.025627 0.021107 0.021107 0.016034 0.007665 0.00505 0.00505	2.5 2 1.5 1 0.5 -0.5 -1 -1.5	m/9	3D do	wnstre 	am velo 	ncity pr	ofile
X 3D da stream	Υ 1 22 4 5 5 7 7 8 8 8 7 7 8 8 8 4 # # # #	U MEAN 1.11433 1.2349 1.36935 1.42576 1.5286 1.5286 1.52413 1.70326 1.70326 1.74215 1.09340 1.66290 1.57772 1.52054 1.52054 1.52054	URMS 0.406375 0.4166375 0.4166375 0.415456 0.412816 0.442366 0.442701 0.442701 0.442701 0.442701 0.442703 0.44263 0.42265 4.042261 0.42261 0.42361 0.422361 0.42561 0.42561 0.42561 0.42561 0.42561 0.42561	U TURBU 5 35.4955 32.9051 7 30.5704 5 29.13918 5 27.69489 1 27.17024 8 26.33066 1 25.57428 1 24.45852 9 25.46465 4 25.70251 9 25.81437 9 26.65036 5 27.7357 1 29.80922	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.01094 -0.015024 -0.015024 -0.015024 -0.01635 -0.01098 -0.010835 2.001835 2.002217	W RMS 0 026483 0.024275 0.100589 0.343183 0.34981 0.366759 0.389591 0.389591 0.393376 0.393376 0.393376 0.393376 0.353433 0.325748	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.3566 22.78148 22.65332 21.85986 22.43376 21.86133 21.2933	UW 0.000463 0.000445 0.001413 0.013304 0.015686 0.025447 0.025301 0.025307 0.025627 0.021107 0.016034 0.007665 0.00505 0.00505 0.00505 0.00505 0.00505	2.5 2 1.5 1 0.5 -0.5 -1 -;.5	m/9	3D do	wnstre 	am velo 	ncity pr	ofile
X 3D da strean	Y 12 1 23 45 75 8 7 8 8 7 8 8 7 8 8 8 8 7 8 8 8 7 8	U MEAN 1.11435 1.23493 1.36935 1.42576 1.5286 1.5286 1.70326 1.70326 1.70326 1.70326 1.70427772 1.52054 1.4247777 1.3329	URMS 0.395545 0.406375 0.418617 0.415456 0.413456 0.42366 0.44281 0.442701 4.0.432701 4.0.432701 4.0.432701 4.0.432701 4.0.432761 0.442665 9.0.420465 9.0.4205 9.0.4205 9.0.4205 9.0.4205 9.0.	U TURBU 5 35.4955 5 32.9051 30.5704 5 29.13918 5 27.69489 1 27.17024 3 26.33666 1 25.57428 1 24.45852 9 25.46406 4 25.70251 9 25.81437 9 26.65036 5 27.7357 1 29.80922 9 30.00026	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01094 -0.00496 0.015024 -0.00496 0.015024 -0.00496 0.015024 -0.01098 -0.01098 -0.010835 -0.01835 -0.001855 -0.01835 -0.001855	W RMS 0 026483 0 024875 0 100589 0 343183 0 343183 0 346759 0 386759 0 38457 0 389591 0 393376 0 396369 0 353433 0 332412 0 325746 0 322546 0 322484	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.3566 22.78148 22.65332 21.65988 21.65988 21.65988 21.65988 21.65988 21.65988 22.437765	UW 0.000463 0.001413 0.01304 0.015886 0.025447 0.025301 0.020307 0.025627 0.021107 0.016034 0.0050505 0.0050505 0.0050505 0.00	2.5 2 1.5 1 0.5 -0 -0.5 -1 -;.5	m/s	3D do	wnstre	am velo 	icity pr	ofile
X 3D da strean	Υ 1 2 3 4 5 6 7 8 5 8 7 8 5 8 7 8 5 8 7 8 5 8 7 8 5 8 7 8 5 8 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4 4	U MEAN 1.11435 1.23493 1.36935 1.42576 1.5286 1.5286 1.74276 1.70326 1.74276 1.70326 1.74276 1.74276 1.74276 1.76909 1.74215 1.52054 1.6290 1.57772 1.52054 1.42107 1.3232 1.421772 1.3232 1.4217772 1.3232 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.42177772 1.421777772 1.42177772 1.42177772 1.4217777772 1.42177777777777777777777777777777777777	URMS 0.395545 0.4(6375 0.418617 0.413456 0.413466 0.423366 0.4432366 0.4432366 0.423366 0.423366 0.423701 0.432701 0.432701 0.44363 0.44363 0.44363 0.44263 0.42265 4.042265 4.042265 2.039877 2.039877 2.0403745 0.	U TURBU 5 35.4955 32.9051 30.5704 5 29.13918 5 27.69489 1 27.17024 3 25.33666 1 25.57428 1 24.45892 9 25.81437 9 25.81437 9 26.65036 5 27.7357 1 29.80922 9 30.00026 9 34.45831	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.00496 0.0015024 -0.00496 0.0015024 -0.01635 -0.01098 -0.01835 -0.0217 5.003161 -0.02327	W RMS 0 026483 0.024275 0.100589 0.343183 0.343183 0.343183 0.343183 0.34575 0.387557 0.38376 0.387557 0.387457 0.363509 0.35343 0.352412 0.32242 0.32242 0.32242 0.32412	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.578148 22.578148 22.85332 21.85935 21.85133 22.9933 22.9933 24.37055 24.37055 24.37055	UW 0.000463 0.000445 0.001413 0.013304 0.015686 0.025447 0.025301 0.025301 0.025627 0.021107 0.021107 0.016034 0.007665 0.000505 0.000505 0.001023 0.001023 0.00906 0.00908	2.5 2 1.5 1 0.5 -0.5 -1 -;.5	m/9	3D do	wnstre	am velo 	icity pr	ofile
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X 3D da strean \$ 6D da strean	Y 1 2 3 4 5 9 7 8 5 米 W # 株 株 株 株 株 株 株 * * * Y	U MEAN 1.11435 1.23493 1.36935 1.42576 1.5286 1.5286 1.70326 1.70326 1.70326 1.74216 1.74216 1.74216 1.74216 1.74216 1.62902 1.74215 1.52054 1.52054 1.42107 1.3229 1.17177 1.3229 1.52054 1.52054 1.55812 4.157767 5.15945 6.159346 7.15796 8.15505 9.1550	URMS URMS 0.423545 0.426375 0.415456 0.415456 0.415456 0.42366 0.42366 0.42266 0.22568 0.21700 0.21508 0.62256 0.22518 0.62326 0.22518 0.23256 0.2355 0.23256 0.235	U TURBU 5 35.4955 5 32.9051 30.5704 5 29.13918 5 27.69489 1 27.7024 3 26.33066 1 25.57428 1 24.45822 9 25.46406 1 29.65036 5 27.7357 9 26.65036 5 27.7357 9 30.00026 9 34.45833 3 40.98837 U TURBU 8 16.2010 5 14.2515 4 13.75686 1 3.7474 15 14.2554 4 13.7548 1 5.5880 37 16.153	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01094 -0.00496 0.015024 -0.00496 0.015024 -0.00496 0.015024 -0.01835 2.002217 -0.01835 2.002217 -0.01835 2.002217 -0.04568 3.002217 4.002526 3.002464 1.003577 4.002553 4.002555	W RMS 0 026483 0 024275 0 100589 0 343183 0 34981 0 366759 0 38457 0 368759 0 38457 0 368759 0 389591 0 389591 0 363509 0 35343 0 332442 0 325746 0 325746 0 32424 0 310017 0 30068 0 03515 ⁴ 0 03515 ⁴ 0 03515 ⁴ 0 03515 ⁴ 0 03515 ⁴ 0 03688 0 0272 ² 0 06818 ² 0 018438 ² 0 018438 ²	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.35743 22.35743 22.3574 22.3505 22.78148 22.85332 21.85986 24.35965 24.35955 W TURBU 24.35955 W TURBU 2.429464 2.39911 1.239842 2.432465 5.1.97080 4.70750 5.1.97080 4.70750 5.1.97080 4.70750 5.1.97080 4.1.5018 5.1.9218 1.1.5018 5.1.9218 3.1.5018 5.1.5018	UW 0.000463 0.000463 0.001413 0.01304 0.015686 0.025447 0.025301 0.025627 0.025627 0.025627 0.025627 0.021107 0.025627 0.02107 0.007663 0.007655 0.003055 0.000555 0.000305 0.000355 0.000355 0.000155 0.00	2.5 2 1.5 1 -0.5 -1 -1 -;.5 2 2.5 2 1.5 1 0.5 0 5 0 5 0 5 0 5 0 5 0 5 0 5 0 5 0 5	m/s	3D do	iownstr iow	am velc	locity pr	rofile
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X 3D da strean 6D da strea	Y 1 2 3 4 5 5 7 5 5 米 米 株 株 株 株 株 株 株 株 株 株 株 株 株 株 株 株	U MEAN 1.11435 1.2349 1.36935 1.42576 1.5286 1.5286 1.5286 1.74276 1.70326 1.74276 1.70326 1.74276 1.70326 1.74276 1.70326 1.74276 1.52054 1.66290 1.57772 1.52054 1.42107 1.32054 1.42107 1.32054 1.42107 1.32054 1.42107 1.32054 1.42107 1.32054 1.42107 1.32054 1.42107 1.5766 1.55955 1.55955 1.55955 1.55955 9.15206 1.5505 9.15206 1.5505 9.15206 1.5505 9.15206 1.5505 9.15206 1.5505 9.15206 1.5505 9.15206 1.5505 9.15206 1.3347 1.3451 # 1.3147 # 1.3147	U RMS 1 0.395545 3 0.4(6375 3 0.4(16477) 5 0.4(15456 3 0.441281 9 0.4(43167) 1 0.432701 4 0.4436701 1 0.4436701 4 0.4436701 4 0.4436701 4 0.4436701 4 0.4420463 9 0.422633 4 0.420463 9 0.423671 2 0.390873 2 0.390873 2 0.390873 2 0.390873 2 0.390873 2 0.390873 2 0.390873 2 0.390873 2 0.390873 2 0.21708 3 0.214400 4 0.21708 5 0.22518 18 0.23326 5 0.249261	U TURBU 5 35.4955 32.9051 30.5704 5 29.13918 5 27.69489 1 27.69489 1 27.77024 1 24.45892 9 25.81437 9 25.81437 9 25.81437 9 25.81437 9 26.65036 5 27.7357 1 29.80922 9 30.00026 9 30.00026 9 30.00026 9 30.00026 9 30.00026 9 30.45831 3 40.99837 U TURBU 8 16.2010 1 13.4888 1 13.7474 1 3.75693 3 13.4888 1 13.7474 1 3.75693 3 13.4888 1 13.7474 1 5.5880 37 16.153 19 16.9724 12 5.53 10 9.1533 39 18.956 1 2.553 1 2.553 1 2.554 1 2.554 1 2.554 1 2.554 1 2.556 1 2.556 1 2.557 1 2.5880 1 3.7474 1 3.75693 3 1.4888 1 3.7474 1 3.75693 3 1.4858 3 1.4858 3 1.4888 3 1.4888 3 1.4888 3 1.55880 3 1.558800 3 1.55880 3 1.558800 3 1.558800 3 1.558800 3 1	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01272 -0.01094 -0.00496 0.05024 -0.00496 0.015024 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.0217 -0.04968 W MEAN 4 -0.02517 4 -0.02517 4 -0.02517 4 -0.02517 4 -0.02517 3 -0.02157 4 -0.02517 4 -0.02517 4 -0.02525 3 -0.02155 4 -0.02572 2 -0.02859 8 -0.02852 3 -0.02858 4 -0.02858 4 -0.02858 4 -0.02858 4 -0.02858 4 -0.02858 4 -0.02858 4 -0.02858 4 -0.02858 5 -0	W RMS 0 026483 0 024275 0 100589 0 343183 0 3491 0 366759 0 393376 0 393577 0 3005157 0 03668 0 0315157 0 03668 0 031422 0 1035157 0 03668 0 031422 0 112713 0 167966 0 178333 0 18304 0 18392 0 18392 0 18392	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.35747 22.23605 22.78148 22.43376 21.85986 22.43376 21.85986 22.43376 21.85986 24.37052 24.37052 31.55957 W TURBU 2.439464 2.399114 1.329844 2.439464 1.329844 2.439464 1.329844 2.439464 1.329844 2.399114 2.399114 2.39914 2.39914	UW 0.000463 0.000445 0.013304 0.013304 0.013804 0.015886 0.025417 0.025301 0.025301 0.025627 0.025627 0.025627 0.025627 0.025627 0.02563 0.0016034 0.007665 0.0016034 0.007655 0.000155 0	2.5 2 1.5 1 0.5 -0.5 -1 -,.5 2 2.5 2 1.5 1 -,.5 -1 -1 -,.5 -1 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -1 -1,.5 -	m/s	3D do	iownstre	am velc 	locity pr	rofile
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X 3D da stream 6D da stream	Y 1 2 3 4 3 8 7 8 9 # # # # # # # # # # # # # # # # # #	U MEAN 1.11435 1.23493 1.36935 1.42576 1.5286 1.70326 1.70326 1.70326 1.70326 1.74215 1.70326 1.74215 1.74215 1.59540 1.52054 1.42075 1.32054 1.42075 1.52054 1.42075 1.52054 1.520	U RMS 0.395545 0.423545 0.4166375 0.415456 0.412617 0.442361 0.443261 0.443261 0.44366 0.442361 0.42361 0.42361 0.432761 4.042361 0.442361 2.0399871 2.0399871 2.0399871 2.0399871 2.0399871 2.0399871 2.0399871 2.0399871 2.0399871 2.0399871 2.0399871 3.030500 U RMS 0.23106 0.21708 0.21708 0.21508 0.21708 0.21508 0.21708 0.21708 0.21708 0.21708 0.21708 0.21328 0.23326 0.24061 0.24061 0.24162 0.24163 <td>U TURBU 5 35.4955 5 32.9051 30.5704 5 29.13918 5 27.69489 1 27.17024 3 26.33066 1 25.57428 1 24.45832 9 25.81437 9 26.65036 5 27.7357 9 26.65036 5 27.7357 9 30.00026 9 34.45831 3 40.98837 U TURBU 8 16.2010- 5 14.2515- 4 14.0029 9 30.00026 9 34.45831 3 40.98837 U TURBU 8 16.2010- 5 14.2515- 4 14.0298 1 13.75693 1 3 13.4888 1 13.7474 15 14.2554 4 15.5880 37 16.153 19 16.9724 12 15.33 39 18.958 31 19.9353 39 20.2025 1 29.2025 1 20.2025 1 29.2025 1 29.</td> <td>W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01094 -0.00496 0.015024 -0.00496 0.015024 -0.00496 0.015024 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.0217 -0.02217 -0.02456 3 -0.02456 3 -0.02456 3 -0.02456 3 -0.02557 4 -0.02553 4 -0.02555 3 -0.02454 4 -0.02553 4 -0.02555 3 -0.02715 4 -0.02553 4 -0.02553 4 -0.02553 4 -0.02553 4 -0.02555 4 -0.02555 5 -0.03785 5 -0.03785 5 -0.04455 5 -0.04455 5</td> <td>W RMS 0 026483 0.024275 0.100589 0.343183 0.34981 0.365759 0.389591 0.393376 0.389591 0.393376 0.389591 0.393376 0.389591 0.393376 0.389591 0.393376 0.389591 0.332412 0.353430 0.353430 0.353430 0.353430 0.326746 0.026722 0.026722 0.02678 0.026782 0.02688 0.026883 0.026782 0.026883 0.026883</td> <td>W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.35605 22.78148 22.43376 21.85937 21.85937 21.85957 W TURBU 2.429464 2.433765 5.31.55957 W TURBU 2.429464 2.439114 1.32984 2.439114 1.32984 2.432169 5.197080 4.70750 5.197080</td> <td>UW 0.000463 0.000463 0.001413 0.013304 0.013304 0.015686 0.025447 0.025301 0.025627 0.025627 0.025627 0.025627 0.021107 0.016034 0.007655 0.00305 0.000155 0.00027 0.00027 0.00027 0.00025 0.00025 0.000155 0.00025 0.0005 0.0005 0.00025 0.00025 0.00025 0.00025 0.0005 0.0005 0.00025 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0</td> <td>2.5 2 1.5 1 0.5 -0.5 -1 -;.5 2 2.5 2 1.5 1 -1.5 -1 -;.5 -1 -1.5 -1.</td> <td>m/s</td> <td>3D do</td> <td>lownstre</td> <td>am velc </td> <td>locity pr</td> <td>rofile</td>	U TURBU 5 35.4955 5 32.9051 30.5704 5 29.13918 5 27.69489 1 27.17024 3 26.33066 1 25.57428 1 24.45832 9 25.81437 9 26.65036 5 27.7357 9 26.65036 5 27.7357 9 30.00026 9 34.45831 3 40.98837 U TURBU 8 16.2010- 5 14.2515- 4 14.0029 9 30.00026 9 34.45831 3 40.98837 U TURBU 8 16.2010- 5 14.2515- 4 14.0298 1 13.75693 1 3 13.4888 1 13.7474 15 14.2554 4 15.5880 37 16.153 19 16.9724 12 15.33 39 18.958 31 19.9353 39 20.2025 1 29.2025 1 20.2025 1 29.2025 1 29.	W MEAN -0.03893 -0.0376 -0.08328 -0.04011 -0.03503 -0.0247 -0.01094 -0.00496 0.015024 -0.00496 0.015024 -0.00496 0.015024 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.0217 -0.02217 -0.02456 3 -0.02456 3 -0.02456 3 -0.02456 3 -0.02557 4 -0.02553 4 -0.02555 3 -0.02454 4 -0.02553 4 -0.02555 3 -0.02715 4 -0.02553 4 -0.02553 4 -0.02553 4 -0.02553 4 -0.02555 4 -0.02555 5 -0.03785 5 -0.03785 5 -0.04455 5	W RMS 0 026483 0.024275 0.100589 0.343183 0.34981 0.365759 0.389591 0.393376 0.389591 0.393376 0.389591 0.393376 0.389591 0.393376 0.389591 0.393376 0.389591 0.332412 0.353430 0.353430 0.353430 0.353430 0.326746 0.026722 0.026722 0.02678 0.026782 0.02688 0.026883 0.026782 0.026883 0.026883	W TURBU 2.376538 1.96562 7.345745 24.07008 22.88313 22.58181 22.57843 22.3547 22.35605 22.78148 22.43376 21.85937 21.85937 21.85957 W TURBU 2.429464 2.433765 5.31.55957 W TURBU 2.429464 2.439114 1.32984 2.439114 1.32984 2.432169 5.197080 4.70750 5.197080	UW 0.000463 0.000463 0.001413 0.013304 0.013304 0.015686 0.025447 0.025301 0.025627 0.025627 0.025627 0.025627 0.021107 0.016034 0.007655 0.00305 0.000155 0.00027 0.00027 0.00027 0.00025 0.00025 0.000155 0.00025 0.0005 0.0005 0.00025 0.00025 0.00025 0.00025 0.0005 0.0005 0.00025 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0005 0.0	2.5 2 1.5 1 0.5 -0.5 -1 -;.5 2 2.5 2 1.5 1 -1.5 -1 -;.5 -1 -1.5 -1.	m/s	3D do	lownstre	am velc 	locity pr	rofile
X 3D da strean 6D da strean	Y 1 2 3 4 3 8 7 8 9 前米市市市市市市市市市市市市市市市市市市市市市市市市市市市市市市市市市市市	U MEAN 1.11435 1.23493 1.36935 1.42576 1.5286 1.5286 1.70326 1.70326 1.70326 1.70326 1.704215 1.704215 1.74215 1.52054 1.52054 1.42107 1.3229 1.17177 1.3229 1.52054 U MEAN U MEAN U MEAN 1.44686 2.152054 U SES 1.55057 3.155812 4.155767 5.159456 1.559346 7.157964 8.15505 9.152064 1.35593 4.155767 5.159456 1.559346 7.157964 8.15505 9.152064 1.34510 4.1345111 4.134511 4.134511 4.134511 4.134511 4.1345111 4.1	U RMS 1 0.395545 3 0.4(6375 3 0.4(6375 3 0.4(15456 3 0.4(2366 9 0.4(2367) 1 0.432701 4 0.4436701 1 0.4436701 1 0.4436701 4 0.442701 4 0.442701 4 0.429263 4 0.42963 9 0.42963 9 0.420463 9 0.420463 9 0.420463 9 0.420463 9 0.420463 9 0.420463 9 0.420463 10 0.390500 10 0.390500 11 0.21708 12 0.21708 13 0.21708 14 0.21353 15 0.221518 18 0.23256 10 0.23563	U TURBU 5 35.4955 32.9051 30.5704 5 29.13918 5 27.69489 1 27.7024 3 26.33666 1 25.57428 1 24.45822 9 25.81437 9 26.65036 5 27.7357 9 26.65036 5 27.7357 9 30.00026 9 34.45833 3 40.98837 U TURBU 8 16.2010 5 14.25154 1 13.75636 1 13.75636 1 13.75636 1 13.7474 15 14.2554 1 13.7474 1 5.5880 1 13.74777 1	W MEAN -0.03893 -0.0376 -0.0328 -0.04011 -0.03503 -0.0247 -0.01094 -0.00496 0.015024 -0.00496 0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.01098 -0.0217 -0.02217 -0.03577 -0.02528 -0.02558 -0.02588 -0.	W RMS 0 026483 0.024275 0.366759 0.343183 0.34981 0.366759 0.389591 0.393376 0.389591 0.393376 0.389437 0.387457 0.387457 0.327464 0.327464 0.327464 0.327464 0.327464 0.326746 0.3267670000000000000000000000	W TURBU 2.376538 1.96562 22.88313 22.58181 22.57843 22.3547 22.2806 22.8313 22.3547 22.2566 22.78148 22.43765 22.43765 22.43765 22.43765 22.43765 24.37055 24.37055 24.37055 24.37055 3.155957 W TURBU 2.429464 2.439414 1.329842 2.432169 5.197000 4.707350 5.197000 4.707350 5.197000 4.15018 5.197000 4.15018 5.197000 4.15018 5.197000 4.15018 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.197000 4.107350 5.1970000 5.1970000 5.1970000 5.1970000 5.1970000 5.1970000 5.1970000 5.1970000000 5.197000000000000000000000000000000000000	uw 0.000463 0.000463 0.001413 0.013304 0.013304 0.015866 0.025447 0.025301 0.025627 0.025627 0.025627 0.025627 0.016034 0.007655 0.007655 0.0007655 0.000906 0.000906 0.000175 0.000175 0.000155 0.000155 0.000155 0.000155 0.000155 0.000155 0.000155 0.000155 0.000155 0.000155 0.000155 0.0002735 0.0002735 0.0002735 0.0002735 0.000159 0.0002735 0.000159 0.000231 0.000231 0.000231 0.000455	2.5 2 1.5 1 0.5 -0.5 -1 -3.5 2.5 2 1.5 1 0.5 -1 -3.5 1 0.5 -1 -3.5 1 0.5 -1 -3.5 -1 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -3.5 -2.5 -1.5 -3.5	m/s	3D do	Iownstre	am velc	locity pr	rofile

SHEAR STRESS AND TURBULENCE INTENSITY IN 1 mm ECCENTRIC BALL OCCLUDER



VELOCITY RAW DATA - 2 mm ECCENTRIC BALL OCCLUDER

	Υl	J MEAN	URMS	U TURBU V	N MEAN W	RMS '	W TURBU d	w		
1D dow	1	-0,54985	0 577471	105.0228	-0.04796	0.041571	7.56048	0.000611	_	4D day and a second second second
stream	2	-0,29099	0.603369	207.3539	-0.02615	0.019604	6.737289	-0.00017	зт	TD downstream velocity profile
	3	-0.02763	0.6342	2295,341	-0,0539	0.08478	306.8432	-0.00037	2.5	nva
	4	0 225388	0,644398	285 9067	-0,1435	0 393515	174 5947	-0.00016	2	
	5	0.505621	0.688493	136 1678	-0 29113	0.687694	136.0099	-0.04627	1.5	B-B-B-B-B
	6	0,756879	0.75349	99 55226	-0.28556	0.794838	105.0153	-0.10020		
		0.901804	0 /68241	85,18932	-0,26464	0.829/59	92.01093	0.11401	1	A BOOM A
	8	0.932309	0.766246	83 46494	-0.141/9	0 973116	100 5675	-0.12023	0.5 +	
	9	0.868189	0,700343	00 43305	-0.02316	0 827617	111 7497	-0.002	0 +	states a later l
	#	0.740509	0.00749	454 3946	-0.00201	0.742776	165 0055	-0.03865	-0.5 0	6 8 10 2 4 16 8
	Ŧ	0.44771	0.690/48	134 2040	0.002034	0 641426	F28 2608	-0.03251		
	#	0.119100	0.634207	240_96/6	-0.03644	0.041433	210 2814	0.04457	11	ar had
	#	-0.245//	0.010/03	200 9200	-0.04427	0.484120	219.2014	0.04981	-1.5 🕹	
	#	-0.53887	0.569105	103 0115	0.012218	0 464129	63.04210	0.03960		
	म	-0.70917	0.344100	10,13337	0.06445	0.432977	112 4241	-0.05309		
	#	-0,46921	0.705120	545 0603	0.003922	0.52/30/	404 1257	-0.00503		
	#	0.152003	0.03213	204 9824	-0.06311	0.467800	121 1040	-0.09807		
~		0.300071	0.790992	204 0024	-0.2520/	0.401033	W TIPAII	-0.03001		
A deve	Т.,	U MEAN	0.607106	62 06262	0.05610	0.065218	6 013949	0.001445		OD day anter an inter the second
2D dow	1	0.918172	0.00/200	EA E4077	-0.03619	0.000210	2 830538	0.000205	3	2D downstream velocity profile
stream	2	1.10334	0.60177	54.54077	-0.03434	0.03133	2.0333330	0.000203	۰T	
	3	1.32056	0.667795	50,3691	-0.03134	0.029739	2.231332	0.000017	2.5 +	and the second s
	4	1 630607	0.6/0202	43,98901	-0.03230	0.003900	37 06969	0.016065	2 +	1 attan N
	2	1.03505/	0.003310	41./1003	-0.0128/	0.00/012	35 45605	0.0100000	1.5	and the second s
	7	1.017368	0.09338	37 0000	0.04002	0.6930+4	35,7200	0.014134	1	and a second and
		1.913399	0.720034	37.90002	0.04298	0.003014	35,1302	0.01003	1	and the second s
	0	1,312000	0.720393	1 30 0/000	0.07240/	0.703/19	30.70031	0.037933	0.5 -	and the second
	3	1 7/1701	0.734/24	> 33 3/223	0.037082	0 722222	41 52122	0.017020	0	
	#	1.741702	0.724342	1 41.39773 5 AE 08601	0.037062	0.723363	41.00122	0.017029	-050	2 4 6 8 10 12 14 16
	- #	1.000070	0713093	1 45 90001	-0.02296	0,709526	40.70000	-0.0013		Radial (mm)
	#	1.302030	0.7171	1 35 04032	-0.03015	0.000340	51.14305	0.01026	-1+	
	#	1.035/91	0.633632	2 80 44608	-0.04637	0.509044	74 04993	-0.03245	-1.5 1	
	#	0.69/125	0.523337	69.44698	-0.07659	0.516213	408 9722	-0.04287		
	#	0.4348/9	0.000000	3 128,9091	-0.09623	0.4/3400	040.0732	-0.03365-		
	#	0.211555	0.503586	3 238.04	-0.10003	0.444808	210.2002	-0.04111		
	Ŧ	0.050711	0,450478	3 888.3177	-0 11614	0.399869	188.3186	-0.03498		X =
	#	-0.0314/	0.40/914	+ 1296,112	-0_114/8	0.30977	964.2675	-0.01857		
X	Y,	UMEAN	URMS	UTURBU	WMEAN	WRMS	WIURBU	uw		i and a second
3D dow	/ 1	1.354082	2 0.439381	1 32,44865	-0.02807	0.021113	1.559196	0.00005		3D downstream velocity profile
stream	2	1,452461	1 0 439864	4 30 28403	-0.0461	0.05006	3,4465/2	0.000224	³ T	103
	3	1.55/544	1 0.463484	4 29 /5/36	-0.03671	0.033524	2.152354	0.000648	2.5	
	4	1.62/295	9 0.479677	/ 29 4/69	-0.05451	0.076847	4./223/9	0.00078	2	A B B B B B B B B B B B B B B B B B B B
	5	1.660864	2 0.499656	a 30.0841/	-0.0396	0.409054	2 24.62891	-0.0029	15	8-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0
	5	1.709383	5 0.508555	9 29 75101	-0.01983	0,419706	24,00300	-0.00822	1.0	B- B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-B-
		1./6549	1 0.524664	4 29/1//5	-0.02017	0.439005	24,66613	-0.0127	1 1	Barne and a
	8	1.80080	1 0.5425	9 30 13049) -0.005/	0.463/64	4 25./5323	-0.013171		
	9	1 800688		C 00 07070	0.00000	0 47 4000	00.04440	0.00700	0.5	State State
	#			5 29 97379	-0.03583	0.474322	2 26 34113	-0.00706	0.5	
		1.75265.	2 0.5502	5 29 97379 7 31.39322	-0 03583	0.474322	2 26.34113	-0.00706	0.5	
	#	1.69085	2 0.5502 3 0.56895	5 29 97379 7 31 39322 8 33 64918	-0.03583 -0.03017 3 -0.02275	0.474322 0.48637 0.502538	2 26.34113 1 27.74774 3 29.72098	-0.00706 -0.01674 -0.01686	0.5 - 0 - -0.5 0	2 4 6 8 10 12 14 16 18 Radial (mm)
	# #	1.69085	2 0.5502 3 0.568956 7 0.57536	5 29 97379 7 31,39322 8 33,64918 3 37,24692	-0 03583 2 -0 03017 3 -0 02275 2 -0 02759	0 474322 0 48637 0 50253 0 49256	2 26.34113 1 27.74774 8 29.72098 6 31.8869	-0.00706 -0.01674 -0.01686 -0.01916	0.5 0 -0.5 0 -1	2 4 6 8 10 12 14 16 18 Radial (mm)
	# # #	1.69085 1.54472 1.39044	2 0.5502 3 0.56895 7 0.57536 8 0.56196	5 29 97379 7 31 39322 8 33 64918 3 37 24692 3 40 41599	-0 03583 -0 03017 -0 02275 -0 02759 -0 03902	0 474322 0 48637 0 502533 0 49256 0 49312	2 26.34113 1 27.74774 8 29.72098 5 31.8869 7 35.46843	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125	0.5 0 -0.5 0 -1 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm)
	# # # # #	1.54472 1.390448 1.2530	2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473	5 29.97379 7 31.39322 8 33.64918 3 37.24692 3 40.41599 3 42.67414	-0.03583 -0.03017 -0.02275 -0.02759 -0.02759 -0.03902 -0.04376	0 474322 0 48637 0 502533 0 49256 0 49312 0 49312	2 26.34113 1 27.74774 8 29.72098 6 31.8869 7 35.46843 7 38.46476	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739	0.5 0 -0.5 0 -1 -1.5	1 2 4 6 8 10 12 14 16 18 Radial (mm)
	* * * * * *	1.5283 1.69085 1.54472 1.39044 1.2530 1.06548	 0.53973 0.5502 0.56895 0.57536 0.561963 0.534733 0.49728 0.49728 	5 29.97379 7 31.39322 8 33.64918 3 37.24692 3 40.41599 3 42.67414 1 46.67167	-0.03583 2 -0.03017 3 -0.02275 2 -0.02759 3 -0.03902 4 -0.04376 2 -0.05538	0 474322 0 48637 0 50253 0 49256 0 49313 0 48198 0 46293	2 26.34113 1 27.74774 8 29.72098 5 31.8869 7 35.46843 7 38.46476 9 43.44845	-0.00706 -0.01674 -0.01685 -0.01916 -0.0125 -0.01739 -0.00287	0.5 0 -0.5 0 -1 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm)
	* # # # # # #	1.69085. 1.54472 1.39044 1.2530 1.06548 0.93832	 0.53973 0.5502 0.56895 0.57536 0.56196 0.53473 0.49728 0.49728 0.45410 	5 29.97379 7 31.39322 8 33.64918 3 37.24692 3 40.41599 3 42.67414 1 46.67165 7 48.3956	 -0 03583 -0 03017 -0 02275 -0 02759 -0 02759 -0 03902 -0.04376 -0 05538 -0 01686 	0 474322 0 48637 0 502533 0 492564 0 49311 0 48198 0 462931 0 433993	2 26.34113 1 27.74774 8 29.72098 5 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25208	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 0.004582	0.5 0 -0.5 0 -1 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm)
	****	1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.81839	 0.53973 0.5502 0.56895 0.57536 0.56196 0.53473 0.49728 0.49728 0.42108 0.42108 	5 29 97379 7 31.39322 8 33.64916 3 37.24692 3 40.41599 3 42.67414 1 46.67162 7 48.3956 9 51.45326	 -0.03583 -0.03017 -0.02275 -0.02759 -0.03902 -0.04376 -0.05538 -0.01665 -0.03115 	0 474322 0 48637 0 502533 0 49256 0 49313 0 48198 0 462933 0 433993 0 36791	2 26.34113 1 27.74774 8 29.72098 6 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25208 9 44.95631	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.0125 -0.01739 -0.00287 0.004582 -0.00346	0.5 0 -0.5 -1 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm)
v	#######	1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.81839 0.65747	 0.33973; 0.5502; 0.56895; 0.57536; 0.55196; 0.55473; 0.49728; 0.49728; 0.42108; 0.42108; 	5 29,97379 7 31,39322 8 33,64916 3 37,24692 3 40,41599 3 42,67414 1 46,67162 7 48,3956 19 51,45326 5 62,12436	 -0.03583 -0.03017 -0.02275 -0.02759 -0.03902 -0.04376 -0.05538 -0.01666 -0.03115 -0.03008 	0 474322 0 48637 0 502533 0 49256 0 49313 0 48198 0 462933 0 462933 0 462933 0 367911 0 15699	2 26.34113 1 27.74774 8 29.72098 6 31.8869 7 35.46843 7 38.46476 9 43.4485 3 46.25208 9 44.95631 1 23.87801	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 0.004582 -0.00346 -0.00175	0.5 0 -0.5 -1 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm)
X	# # # # # # # Y	1.69085 1.69085 1.54472 1.390444 1.2530 1.06548 0.93832 0.81839 0.65747 U MEAN	2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.49728 2 0.45410 2 0.42108 2 0.4084 U RMS	5 29,97376 31,39322 33,64916 3 37,24692 3 40,41595 3 42,67414 4 46,67162 7 48,3956 19 51,45326 5 62,12436 0 TURBU	 -0.03583 -0.03017 -0.02275 -0.02759 -0.03902 -0.03902 -0.04376 -0.04376 -0.05538 -0.01666 -0.03115 -0.03008 W MEAN 	0.474322 0.48637 0.502533 0.492566 0.49313 0.48198 0.462933 0.462933 0.462933 0.462933 0.463993 0.367919 0.15699 W RMS	2 26.34113 1 27.74774 8 29.72098 6 31.8869 7 35.46843 7 38.46476 9 43.4485 3 46.25208 9 44.95631 1 23.87801 W TURBL	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 0.004582 -0.00346 -0.00175	0.5 0 -0.5 0 -1 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov	# # # # # # * * * * * * * * * * * * * *	1.69085 1.69085 1.54472 1.39044 1.2530 1.065482 0.93832 0.81839 0.65747 U MEAN 1.43450	2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.49728 2 0.45410 2 0.42108 2 0.42108 2 0.4084 U RMS 9 0.33006	5 29,97379 7 31,39322 8 33,64916 3 37,24692 3 40,41599 3 42,67414 1 46,67167 7 48,3956 19 51,45326 5 62,12436 U TURBU 7 23,00907 2 3,00907 1 45,000 1 45,0000 1 45,0000 1 45,0000 1 45,0000 1 45,0000 1 45,0000 1 45,000	 -0.03583 -0.03017 -0.02275 -0.02759 -0.03902 -0.04376 -0.04376 -0.05538 -0.01666 -0.03115 -0.03008 W MEAN 2 -0.07561 	0.474322 0.48637 0.502533 0.492566 0.49313 0.48198 0.462933 0.462933 0.462933 0.462933 0.367919 0.15699 W RMS 0.078055	2 26.34113 1 27.74774 8 29.72098 5 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25208 9 44.95631 1 23.87801 W TURBL 7 5.441385	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 0.004582 -0.00346 -0.00175 J uw	0.5 - 0 - 0.5 0 - 1 - 1 - 1.5 -	2 4 6 8 10 12 14 16 18 Radial (mm) 6D downstream velocity profile
X 6D dov stream	**************************************	1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.81839 0.65747 U MEAN 1.43450 2.1.54228	2 0.5502 3 0.56895. 7 0.57536: 8 0.56196: 6 0.53473 9 0.49728 2 0.49728 2 0.49728 2 0.42108 2 0.42108 2 0.4084 U RMS 9 0.33006 8 0.22875	5 29.9737; 7 31.39322; 8 33.6491; 3 37.24692; 3 40.41599; 3 42.67414; 1 46.6716; 7 48.3956; 9 51.45326; 5 62.12436; U TURBU; 7 23.0090; 6 14.8322;	 -0.03583 -0.03017 -0.02275 -0.02759 -0.03902 -0.04376 -0.04376 -0.05538 -0.01666 -0.03105 -0.03008 W MEAN -0.03594 	0.474322 0.48637 0.502534 0.492566 0.49313 0.48198 0.462933 0.462933 0.367911 0.15699 W RMS 0.07805 0.03695	2 26.34113 1 27.74774 3 29.72094 6 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25208 9 44.95631 1 23.87801 W TURBL 7 5.441389 9 2.396397	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 0.004582 -0.00346 -0.00175 Juw 0.000176 -0.00021	0.5	6D downstream velocity profile
X 6D dov stream	###### *******************************	1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.81839 0.65747 U MEAN 1 1.43450 2 1.54228 3 1.55544	2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.49728 2 0.45410 2 0.42108 2 0.42108 2 0.42408 4 U RMS 9 0.33006 8 0.22875 8 0.21810	5 29,9737; 31.3932; 8 3 37,2469; 3 37,2469; 3 42,67414; 1 46,6716; 7 48,395; 19 51,4532; 5 62,12436; UTURBU; 7 16 14,8322; 12 14,021;	 -0.03583 -0.03017 -0.02275 -0.02759 -0.03902 -0.04376 -0.04376 -0.05538 -0.01666 -0.03115 -0.03008 W MEAN -0.07561 -0.03994 -0.03994 -0.03994 -0.03994 -0.03994 	0.474322 0.48637 0.50253 0.49256 0.4931 0.48198 0.46293 0.46293 0.46293 0.46293 0.43399 0.43399 0.15699 W RMS 0.15699 W RMS 0.07805 0.03695 0.03695	2 26.34113 1 27.74774 8 29.72094 6 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25206 9 44.95631 1 23.87801 W TURBL 7 5.441385 9 2.396397 7 6.299614	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 0.004582 -0.00346 -0.00175 Juw 0.000176 Juw	0.5 0 -0.5 -1 -1.5 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm) 6D downstream velocity profile m/s
X 6D dov stream	**************************************	1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.81839 0.65747 U MEAN 1 .43450 2 1.54228 1.55544 1.56288	2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.49728 2 0.45410 2 0.42108 2 0.4084 U RMS 9 0.33006 8 0.22875 8 0.21810 4 0.21590 5 0.21590	5 29,9737; 31.3932; 3 3 3,2469; 3 3,2469; 3 3,2469; 3 40,4159; 3 42,67414; 1 46,67165; 17 48,3956; 19 51,45326; 17 23,0090; 17 23,0090; 16 14,8322; 12 14,0218; 19 13,8144;	 -0.03583 -0.03017 -0.02275 -0.03902 -0.04376 -0.05538 -0.01666 -0.03115 -0.03008 W MEAN -0.07561 -0.03594 -0.03594 -0.03594 -0.03791 -0.03791 	0,474322 0,48637 0,50253 0,49258 0,49313 0,48198 0,46193 0,46198 0,46293 0,46399 0,46399 0,46399 0,46399 0,46399 0,46399 0,46399 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,47402 0,4758 0,49258 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,49395 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,0493 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,04939 0,07000 0,07000 0,07000 0,07000 0,07000 0,07000 0,00000000	2 26.34113 1 27.74774 3 29.72098 6 31.8869 7 35.46843 7 38.464476 9 43.44845 3 46.25208 9 44.95631 1 23.87801 W TURBL 7 5.441389 9 2.396397 7 6.299614 7 6.567127	-0.00706 -0.01674 -0.01688 -0.01916 -0.0125 -0.00287 0.004582 -0.00346 -0.00175 J uw 0.000176 -0.000176 -0.000176 -0.000176	0.5 0 -0.5 -1 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5	6D downstream velocity profile
X 6D dov stream	######## wn	1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.81839 0.65747 U MEAN 1.43450 2.1.54228 3.1.55544 1.56288 3.1.55544	2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.49728 2 0.42108 2 0.42108 2 0.42108 2 0.422108 2 0.422108 2 0.422108 8 0.22875 8 0.21810 4 0.21590 1 0.21353 2 0.21552 2 0.2552 2 0.5502 2 0.45786 2 0.42108 2 0.422108 2 0.422108 2 0.422108 2 0.422108 2 0.422108 2 0.42215 2 0.22875 2	5 29,9737; 31.3932; 8 33,6491; 3 33,2469; 3 340,41599; 3 342,67414; 48,6716; 1346,6716; 5 139,22; 5 146,6716; 5 15,14532; 5 16,14532; 5 1748,306; 14,8322; 12148; 13,8144; 173814; 13,7182;	 -0.03583 -0.03017 -0.02275 -0.03902 -0.03902 -0.04376 -0.05538 -0.01666 -0.03115 -0.03008 W MEAN -0.07561 -0.03594 -0.03791 -0.03417 	0,474322 0,48637 0,50253 0,49258 0,49311 0,48198 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46393 0,46395 0,66614	2 26.34113 1 27.74774 3 29.72098 6 31.8869 7 35.46643 7 38.46476 9 43.44845 3 46.25208 9 44.95631 1 23.87801 W TURBL 7 5.441386 9 2.396397 7 6.29614 7 6.567127 2 4.249185	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.0125 -0.00287 -0.00287 -0.00346 -0.00175 J uw -0.000176 -0.000176 -0.000176 -0.000176 -0.00014 -0.00058	0.5 0 -0.5 -1 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5	2 4 6 8 10 12 14 16 18 Radial (mm) 6D downstream velocity profile m/s
X 6D dov stream	• • • • • • • • • • • • • • • • • • •	1.5283. 1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.65747. U MEAN 1.43450 2.1.54228 3.1.55544 4.1.56559 3.1.5541	2 0.5502 3 0.56895 7 0.57536 8 0.56196 9 0.45473 9 0.49728 2 0.45410 2 0.42108 2 0.42108 9 0.33006 8 0.22875 8 0.22875 8 0.21810 1 0.21323 1 0.21323 2 0.21323 3 0.5502 1 0.21323 1 0.2132 1	5 29,9737; 31.3932; 8 33,6491; 3 33,2469; 3 340,4159; 42,67414 46,6716; 48,3956; 5 62,1432; 9 51,45326; 7 48,3956; 62,12436; UTURBU; 7 23,0090; 16 44,83224; 12 14,0211; 19 13,8144; 17 13,7182; 19 13,8098;	 -0.03583 -0.03017 -0.02275 -0.03902 -0.03902 -0.04376 -0.05538 -0.03115 -0.03008 W MEAN -0.03594 -0.03791 -0.03791 -0.05568 	0,474322 0,48637 0,50253 0,49256 0,4931 0,48198 0,46293 0,04595 0,04595 0,04595 0,04595 0,04595 0,04595 0,04595 0,04595 0,04595 0,04595 0,04595 0,0780	2 26.34113 1 27.74774 3 29.72094 6 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25206 9 44.95631 1 23.87801 W TURBU 7 5.441385 9 2.396397 7 6.567127 2 4.249187 2 5.10988	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.0125 -0.00287 0.004582 -0.00346 -0.00175 Juw 0.000176 -0.00017 -0.00014 -0.00018 -0.00018	0.5 0 -0.5 -1 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5	6D downstream velocity profile
X 6D dov stream	: ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ; ;	1,69085 1,69085 1,69085 1,65472 1,39044 1,06548 0,93332 0,81839 0,65747 U MEAN 1,43450 1,15428 3,1,55544 4,1,56288 5,1,55628 5,1,5544 1,55447	2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.49728 2 0.45410 2 0.42108 2 0.42108 0 0.4208 0 0.4208 8 0.22875 8 0.21810 4 0.21353 1 0.21323 2 0.21768	5 29.97372 7 31.39322 8 33.64916 3 37.24692 3 40.41595 3 40.41595 3 42.67414 1 46.67166 17 48.3956 19 51.45326 5 62.12438 UTURBU 7 13 814 19 13.8144 19 13.8144 19 13.8144 19 13.8098 18 14.307	 -0.03583 -0.03017 -0.02275 -0.03902 -0.04376 -0.04376 -0.05538 -0.01666 -0.03105 -0.03008 WMEAN -0.03594 -0.03791 -0.03791 -0.05588 -0.03964 -0.03644 	0.474322 0.48637 0.50253 0.49256 0.49313 0.48198 0.46293 0.46293 0.46293 0.46293 0.46293 0.46293 0.46293 0.46293 0.46293 0.46293 0.46293 0.466791 0.15699 W RMS 0.07805 0.03695 0.07805 0.06614 0.10263 0.06614 0.07890 0.067789	2 26.34113 1 27.74774 8 29.72094 6 31.8869 7 35.46843 7 35.46843 7 38.46476 9 43.4485 3 46.25208 9 44.95631 1 23.87801 W TURBL 7 5.441385 9 2.396397 7 6.567127 2 4.249187 2 5.109881 3 10.33752	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 -0.00346 -0.00175 Juw 0.000176 -0.000176 -0.000176 -0.000176 -0.00014 -0.00018 -0.00014 -0.00058 -0.00115 2 -0.00199	0.5 0 -0.5 0 -1 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -1.5 -	2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov stream);;; /, /, /, /, /, /, /, /, /, /, /, /, /,	1,69085 1,69085 1,69085 1,69085 1,69044 1,2530 1,06548 0,93332 0,81839 0,65747 U MEAN 1,43450 2,1,5428 3,1,5544 4,1,56288 5,1,55659 3,1,5441 7,1,52147 3,1,5633	0.33973 2 0.5502 3 0.56895 7 0.57536. 8 0.56196. 6 0.53473 9 0.49728 2 0.45410 2 0.42108 2 0.42188 9 0.33006 8 0.22875 8 0.21590 1 0.21323 2 0.21768 9 0.22240	5 29,9737; 31.3932; 3 3 3.6491; 3 3.72463; 3 40.4159; 3 40.4159; 3 42.67414; 1 46.67165; 17 48.3956; 19 51.45326; 17 23.0090; 16 14.8322; 17 13.8144; 17 13.8144; 19 13.8098; 18 14.307; 19 13.8098; 18 14.307; 14 8.314;	 -0.03583 -0.03017 -0.02275 -0.03902 -0.03902 -0.04376 -0.0538 -0.01666 -0.03115 -0.03008 W MEAN -0.07561 -0.03594 -0.03594 -0.03591 -0.03591 -0.04379 -0.04371 -0.03964 -0.03964 -0.03964 -0.03264 	0,474322 0,48637 0,50253 0,49258 0,49311 0,48198 0,46293 0,43399 0,43399 0,43399 0,36791 0,15699 W RMS 0,07605 0,03695 0,03695 0,03695 0,03695 0,00614 0,07890 0,07805 0,07864 0,07890	2 26.34113 1 27.74774 3 29.72098 5 31.8869 7 35.46843 7 38.46476 9 43.44845 9 43.44845 9 43.44845 9 43.45531 1 23.87801 W TURBL 9 2.396397 7 5.441385 9 2.396397 7 6.299614 7 6.567127 2 4.249185 5 109881 3 10.33757 4 11.21822 1 1.21822 1 1.21822 1 1.21822 1 1.21822 1 1.2182 1 1 1.2182 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 -0.00346 -0.000175 -0.000176 -0.000176 -0.000176 -0.000176 -0.00018 -0.00018 -0.00018 -0.00018 -0.00018 -0.00018	0.5 0 -0.5 -1 -1.5 -1.5	6D downstream velocity profile
X 6D dov stream	;;;;,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	1.69085 1.69085 1.54472 1.39044 1.2530 1.06548 0.93832 0.81839 0.65747 U MEAN 1 .43450 2 .54248 3 .155544 4 .156589 5 .1.55659 5 .1.55441 7 .152147 3 .150633 3 .1.47806	0 0.33973 0 0.5502 0 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.494728 2 0.45410 2 0.42108 9 0.33006 8 0.22875 8 0.21350 1 0.21323 2 0.21768 9 0.32091	5 29,97375 31.39322 33.64918 3 33.64918 3 37.24632 3 40.41599 3 42.67414 11 46.67165 13 52.67414 14 46.67165 17 48.3956 19 51.45326 17 13.09021 16 14.83224 12 14.0211 19 13.8144 13 13.8098 18 14.3071 18 14.30731 14 15.6225	 -0.03583 -0.03017 -0.02275 -0.03902 -0.03902 -0.04376 -0.05538 -0.01666 -0.0115 -0.03008 W MEAN -0.03594 -0.03594 -0.03594 -0.03791 -0.03964 -0.03964 -0.03964 -0.03964 -0.03964 -0.03964 -0.03964 -0.03964 -0.03964 	0,474322 0,48637 0,50253 0,49256 0,49315 0,48198 0,46293 0,46393 0,46393 0,46393 0,46393 0,16699 W RMS 0,07805 0,03695 0,07805	2 26.34113 1 27.74774 2 97.2098 6 31.8669 7 35.46843 7 38.46476 9 43.44845 3 46.25208 9 44.95631 1 23.87801 W TURBL 7 5.441385 9 2.396397 7 6.29614 7 6.567127 2 4.249187 3 10.33755 4 11.21822 1 22.2573 	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 -0.004582 -0.00346 -0.00175 Juw -0.000176 -0.000176 -0.000174 -0.00012 -0.00014 -0.00018 -0.00012 -0.00199 2 -0.00199 2 -0.00512	0.5 0 -0.5 -1 -1.5	6D downstream velocity profile
X 6D dov stream	¥ ; } ; € ;	1,69085 1,69085 1,69085 1,69085 1,2530 1,06548 0,93832 0,65747 U MEAN 1,143450 2,1,54228 3,1,5544 1,55659 5,1,5441 7,1,52147 3,1,5643 3,1,47806 1,144338	0 0.3397.3 0 5502 3 0.56196 0.56196 0.56196 0 0.54736 9 0.49728 2 0.45410 2 0.42108 2 0.42108 9 0.33066 8 0.22875 8 0.21810 1 0.21590 1 0.21323 2 0.24768 9 0.23091 1 0.21323 2 0.22807 1 0.21323 2 0.24203 3 0.23091 1 0.23091 14 0.23676	5 29,9737; 31.3932; 3 3 3.2469; 3 3.2469; 3 3.2469; 3 40.4159; 3 42.6741; 46.6716; 48.395; 9 51.4532; 9 51.4532; 17 23.0090; 16 48.392; 17 13.8144; 17 13.8144; 17 13.8098; 18 14.307; 14 15.6225; 19 13.8098; 14 14.8731; 15 6225; 14 14.6731;	 -0.03583 -0.03017 -0.02275 -0.03902 -0.04376 -0.05538 -0.01666 -0.03115 -0.03002 W MEAN -0.03594 -0.03594 -0.03791 -0.039791 -0.03964 -0.03964 -0.03964 -0.03964 -0.03254 -0.03254 -0.03264 -0.03264 -0.03264 -0.03264 	0,474322 0,48637 0,50253 0,49256 0,49315 0,48198 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,10269 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07890 0,17728 0,07890 0,07800 0,07800 0,07800 0,07800 0,07800 0,07800 0,07800 0,07800 0,07800 0,07800 0,07800 0,07800 0,0780000000000	2 26.34113 1 27.74774 3 29.72098 6 31.8869 7 35.46643 7 38.46476 9 43.44845 3 46.25208 9 44.95631 1 23.87801 W TURBL 7 5.441385 9 2.396397 7 6.299614 7 6.299614 7 6.299614 7 6.299614 7 6.299614 1 0.33752 2 1.09881 3 10.33752 1 12.2573 6 12.7510	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 -0.00346 -0.00175 Juw 0.000175 -0.000176 -0.000176 -0.000176 -0.000175 2-0.00018 -0.00115 2-0.00192 2-0.00512 1-0.0064	0.5 0 -0.5 0 -1 -1 -1.5 3 2.5 2 1.5 1 -0.5 0 -1 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1 -1 -1.5 -1 -1 -1 -1.5 -1 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1.5 -1.	6D downstream velocity profile
X 6D dov stream	* * * ? ! : • • : • : • • • * * * * * * * * * * *	1,69085 1,69085 1,69085 1,69085 1,65472 1,39044 1,06548 0,93332 0,81839 0,65747 U MEAN 1,43450 2,155544 1,55544 1,55544 1,55544 1,55247 3,15563 3,147806 1,4438 1,4438 1,41291	0 33973 2 0.5502 3 0.56196 6 0.57536 6 0.54733 9 0.49728 2 0.45410 2 0.42108 2 0.42108 9 0.33006 8 0.22875 8 0.21590 1 0.21323 2 0.21323 3 0.223091 3 0.23091 4 0.2377	5 29,9737; 31.3932; 3 8 33,6491; 3 37,2469; 3 40,4159; 3 42,6741; 14 46,6716; 9 51,4532; 9 51,4532; 9 51,4532; 10 48,3956; 12 14,0214; 12 14,0214; 13 713,7182; 13 13,8098; 18 14,3071; 14 14,8731; 15 5225; 16 6037; 13 16,8255;	 -0.03583 -0.03017 -0.02275 -0.03902 -0.03902 -0.04376 -0.05538 -0.03115 -0.03008 W MEAN -0.03594 -0.03791 -0.03791 -0.03791 -0.03594 -0.03791 -0.03594 -0.03791 -0.03594 -0.03791 -0.03594 -0.03791 -0.03791 -0.03791 -0.039437 -0.03254 -0.03254 -0.03254 -0.03264 	0,474322 0,48637 0,50253 0,49256 0,4931 0,48198 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,16569 0,07805 0,0780	2 26.34113 1 27.74774 3 29.72094 6 31.8869 7 35.46843 7 35.46843 7 38.46476 9 43.44845 3 46.25206 9 44.95631 1 23.87801 W TURBU 7 5.441385 9 2.396397 7 6.567127 2 4.249187 2 5.109881 3 10.33755 4 11.21822 1 12.2573 6 12.7510 2 3.4690 4 4.495 4 4.495 4	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 3 0.004582 -0.00346 -0.00175 Juw 9 0.000176 -0.000176 -0.000176 -0.00018 1 -0.00018 2 -0.00115 2 -0.00199 2 -0.00572 1 -0.00572 1 -0.0064 5 -0.00432	0.5 0 -0.5 0 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1.5 -	6D downstream velocity profile m/s 6D downstream velocity profile 7 2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov stream	* * * * ? ?	1,69085 1,69085 1,69085 1,69085 1,69044 1,2530 1,06548 0,93332 0,81839 0,65747 U MEAN 1,43450 2,1,5428 3,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,56288 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,5544 4,1,5544 5,1,55445,1,5544 5,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,55445,1,5544 5,1,55445,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,55445,1,5544 5,1,55445,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,5544 5,1,55445,1,55445,1,5544 5,1,55445,1,554455,1,554455,1,554455,1,5	0 33973 2 0.5502 3 0.56196 6 0.57536 8 0.56196 0 0.4728 2 0.45410 2 0.42108 2 0.42108 2 0.42108 9 0.33006 8 0.22875 8 0.21590 1 0.21323 2 0.21768 9 0.23001 1 0.21323 2 0.21768 9 0.23001 1 0.21323 2 0.21461 1 0.21323 2 0.2240 13 0.23071 14 0.23676 4 0.23937 19 0.23937	5 29,9737; 31.3932; 33.3932; 3 37.2463; 3 40.4159; 3 40.4159; 3 42.67414; 1 46.67166; 7 48.3956; 9 51.45326; 5 62.12436; 17 23.0090; 16 14.83224; 17 13.8144; 17 13.8144; 17 13.8144; 13 14.43224; 14.0211; 13.8144; 17 13.8144; 13 14.4307; 13 14.4307; 14 8731; 11 15.6225; 13 16.4037; 14 8255; 13 16.8255; 14 17.3475;	 -0.03583 -0.0317 -0.02275 -0.03902 -0.03902 -0.04376 -0.0538 -0.01666 -0.01666 -0.03008 J WMEAN -0.03594 -0.03964 -0.03864 -0.03865 -0.03865 -0.03865 -0.03872 	0,474322 0,48637 0,50253 0,49256 0,4931 0,48198 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46399 0,46293 0,46399 0,15699 W RMS 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07805 0,07890 0,15728 0,16898 0,16898 0,18117 0,18444 0,018917 0,018444 0,018917 0,018444 0,019905 0,0	2 26.34113 1 27.74774 3 29.72098 6 31.8859 7 35.46843 7 38.46476 9 43.44845 3 46.25208 9 43.44845 9 43.44845 9 43.44845 9 43.46863 9 43.46863 9 4.295631 1 2.387801 W TURBL 5.1098613 7 6.299614 7 6.299614 7 6.299614 7 6.567122 2 4.249183 3 10.33752 4 12.25731 3 10.33752 4 12.25731 3 13.46900 3 13.9194	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 -0.00287 -0.00346 -0.00175 Juw -0.000176 -0.000176 -0.000176 -0.000176 -0.000176 -0.000175 2 -0.00115 2 -0.00199 2 -0.00512 1 -0.00643 5 -0.00432 1 -0.00481	0.5 0 -0.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1.5 -1.	6D downstream velocity profile m/s 2 4 6 8 10 12 14 16 18 Radial (mm) 2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov stream	* * * * * ? : . • ? • . • * * * * * * * * * * * * * * * * *	1,69085 1,69085 1,69085 1,69085 1,69085 1,54472 1,39044 1,2530 0,65747 UMEAN 1,43450 2,1,5428 3,1,55544 4,1,56288 5,1,55659 3,1,5441 7,1,52147 3,1,5643 3,1,5441 7,1,52147 3,1,5643 3,1,5444 1,1,52147 3,1,5643 3,1,5444 1,1,52147 3,1,52147 3,1,5643 3,1,5444 1,1,52147 3,1,5643 3,1,5444 1,1,52147 3,1,5444 1,55544 4,1,55747 4,1,57474,1,5747 4,1,7747 4,1,77474,1,5747 4,1,77474,1,77474,1,7747 4,1,77474,1,7747 4,1,7	0.33973 2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.54733 9 0.49728 2 0.45410 2 0.42108 2 0.42108 2 0.42108 9 0.33006 8 0.22875 8 0.21350 1 0.21323 2 0.21323 1 0.21323 2 0.21323 1 0.21323 1 0.21323 1 0.21323 1 0.23676 4 0.23676 4 0.23937 1 0.24525	5 29.9737; 31.39322; 33.6491; 3 33.6491; 3 37.2463; 3 40.4159; 3 42.6741; 1 46.67165; 13 42.6741; 14 46.67165; 17 48.3956; 19 51.45326; 17 23.0090; 16 14.8322; 12 14.0211; 19 13.8144; 17 13.7182; 19 13.8098; 39 13.8098; 38 14.3071; 11 15.6225; 39 16.4037; 13 16.4255; 14 8731; 15 6225; 13 16.4255; 13 16.8255; 14 17.3475; 15 18.2045;	 -0.03583 -0.03017 -0.02275 -0.02759 -0.03902 -0.04376 -0.05538 -0.01666 -0.03115 -0.03008 J W MEAN -0.03594 -0.03964 -0.03964 -0.03962 -0.03972 -0.03972 -0.03973 	0,474322 0,48637 0,50253 0,49256 0,49256 0,48198 0,46293 0,46393 0,46393 0,46393 0,46393 0,03695 0,03695 0,03695 0,07805 0,07805 0,07805 0,03695 0,06614 0,07890 0,07890 0,015728 0,015728 0,018177 0,018404 0,018404 0,01893 0,01893 0,018177 0,018404 0,01893 0,01993 0,0199	2 26.34113 1 27.74774 3 29.72098 6 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25208 9 44.95631 1 23.87801 WTURBU 5.441386 9 2.396397 6 5.67127 2 4.249187 3 10.33752 4 11.21822 1 12.25733 6 13.46904 3 13.39194 9 15.27723	-0.00706 -0.01686 -0.01916 -0.01916 -0.0125 -0.0125 -0.004582 -0.00346 -0.00175 Juw -0.000176 -0.000176 -0.000174 -0.00014 -0.00014 -0.00015 2 -0.00199 2 -0.00199 2 -0.00512 1 -0.00432 1 -0.00432 5 -0.00431 5 -0.00378	0.5 0 -0.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1 -1 -1 -1 -1 -1 -1 -1 -1	6D downstream velocity profile m/s 2 4 6 8 10 12 14 16 18 Radial (mm) 2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov stream	,	1.69085 1.69085 1.69085 1.69085 1.25472 1.39044 1.2530 1.06548 0.93332 0.81839 0.65747 U MEAN 1.43450 2.1.54248 1.555544 1.555544 1.55559 3.1.55444 1.55559 3.1.55444 1.55559 3.1.55447 1.52147 1.50633 3.1.47806 1.44338 1.41291 1.37964 1.37964 1.37942 1.37944 1.37944 1.37944 1.37944 1.37944 1.37944 1.379444 1.37944 1	0 0.33973 2 0.5502 3 0.56895 7 0.57536 8 0.56196 6 0.53473 9 0.494728 2 0.45410 2 0.45410 2 0.4024 U RMS 9 9 0.33006 8 0.22875 8 0.21353 1 0.21323 2 0.24768 9 0.33006 4 0.23031 1 0.213233 2 0.24768 9 0.23091 4 0.23076 4 0.23977 9 0.23937 1 0.24522 3 0.23775	5 29,9737; 31.3932; 3 3 3.6491; 3 3.72469; 3 3.72469; 3 3.2,2469; 3 40,4159; 3 42,6741; 14 46,6716; 17 48,3956; 19 51,45326; 10 14,8322; 12 14,0211 19 13,8144; 17 13,8098; 18 14,307; 14 307; 14 15,6225; 39 16,4037; 11 15,6225; 39 16,4037; 11 15,6225; 39 16,8255; 31 18,2045; 32 14,307; 13 8,2045; 31 18,2045; 31 18,2045; 39 18,2726;	 -0.03583 -0.03017 -0.02275 -0.03902 -0.03902 -0.04376 -0.05538 -0.01666 -0.01666 -0.03008 J W MEAN -0.03594 -0.03254 -0.03264 -0.03264 -0.03264 -0.03928 	0,474322 0,48637 0,50253 0,49256 0,49315 0,48198 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,15699 W RMS 0,07805 0,03695 0,03695 0,007805 0,000500000000	2 26.34113 1 27.74774 3 29.72098 6 31.8669 7 35.46843 7 38.46476 9 43.44845 3 46425208 9 44.95631 1 23.87801 W TURBL 7 5.441385 9 2.396397 7 6.29614 7 6.267127 2 4.249187 2 4.249187 3 10.33757 1 12.2573 1 12.2573 1 12.2573 1 12.2573 1 12.2573 1 13.46900 7 13.91944 1 5.2772 1 16.3802 1 16.380	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 -0.004582 -0.004582 -0.000175 -0.000176 -0.000176 -0.000176 -0.000176 -0.000175 2 -0.00014 -0.000199 2 -0.00512 1 -0.00512 1 -0.00512 1 -0.00542 1 -0.00481 5 -0.00388 2 -0.00388 2 -0.00385 2 -0.00355 2 -0.00385 2	0.5 0 -0.5 0 -1 -1.5 -1.	6D downstream velocity profile m/s 2 4 6 8 10 12 14 16 18 Radial (mm) 2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov stream	1 w v v v v v v v v v v v v v v v v v v	1,69085 1,69085 1,69085 1,54472 1,39044 1,2530 1,06548 0,81839 0,65747 U MEAN U MEAN 1,43450 2,15428 3,155544 1,55244 3,155544 1,55247 3,155633 1,5441 7,152147 3,150633 1,47406 1,44338 4,14291 1,37944 1,	0 0.33973 2 0.5502 3 0.56196 6 0.57536 6 0.57536 6 0.54173 9 0.49728 2 0.45410 2 0.45410 2 0.42108 2 0.42108 9 0.33006 8 0.22875 8 0.22810 0 0.21323 1 0.21323 1 0.21323 3 0.23091 14 0.23676 4 0.2377 19 0.23775 10 0.23426 3 0.23775 3 0.23456 3 0.23456	5 29,9737; 31.3932; 8 33.6491; 3 33.72469; 3 340.4159; 3 340.4159; 42.67414 45.6716; 48.3956; 9 51.45326; 9 51.45326; 9 51.45326; 9 51.45326; 9 13.8144; 17 13.8098; 18 14.0211; 15 6225; 39 16.4037; 13 15 39 16.4037; 11 15 39 16.4037; 73 16 8245; 39 16.4037; 71 17.3475; 31 8.2045; 39 18.2045; 39 18.43	 -0.03583 -0.03017 -0.02275 -0.03902 -0.03902 -0.04376 -0.05538 -0.0362 -0.03115 -0.03068 J W MEAN -0.03594 -0.03791 -0.03979 -0.034137 -0.03594 -0.03968 -0.03254 -0.03254 -0.03254 -0.03264 -0.03264<	0,474322 0,48637 0,50253 0,49256 0,49315 0,48198 0,46293 0,46293 0,46293 0,46293 0,46393 0,46393 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,16299 W RMS 0,07805 0,03695 0,00780 0,10263 0,00614 0,10289 0,16298 0,16298 0,18117 0,18404 0,18404 0,18404 0,182054 0,0286464 0,02864 0,02864 0,00	2 26.34113 1 27.74774 3 29.72098 6 31.8869 7 35.46843 7 35.46843 9 44.95631 1 23.87801 W TURBL 7 5.441385 9 2.396397 7 6.567127 2 4.249187 2 5.109861 3 10.33755 1 12.2573 1 12.2573 1 12.2573 1 12.2573 1 12.2573 1 3.9194 9 15.27722 1 16.3802 3 18.7306	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.0125 -0.00287 -0.00287 -0.00346 -0.00175 -0.000176 -0.000176 -0.000176 -0.000176 -0.00018 -0.00018 -0.00192 -0.00052 1 -0.0052 1 -0.0052 1 -0.0054 5 -0.0036 5 -0.0036 9 -0.00561	0.5 0 -0.5 0 -1 -1 -1.5 2 2.5 2 -1 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1.5 -1 -1 -1.5 -1.5	6D downstream velocity profile m/s 2 4 6 8 10 12 14 16 18 Radial (mm) 2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov stream	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1,69085 1,69085 1,69085 1,69085 1,54472 1,39044 1,2530 1,06548 0,33322 0,81839 0,65747 U MEAN 1,43450 2,1,55444 1,552447 3,1,5544 1,552447 3,1,55244 3,1,55244 3,1,55244 3,1,55244 3,1,55244 3,1,55244 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,52147 3,1,56288 5,1,5544 1,5441 7,1,52147 3,1,56288 5,1,5544 1,5441 7,1,52147 3,1,5744 1,5747 1,37984 1,37725 1,37422 1,37725 1,2,5757 1,2,2775 1,2	0 33973 2 0.5502 3 0.56196 6 0.57536 8 0.56196 0 0.54733 9 0.49728 2 0.45410 2 0.45410 2 0.42108 9 0.33006 8 0.22875 8 0.21353 1 0.21353 1 0.21323 2 0.21768 9 0.23001 4 0.23071 3 0.23071 1 0.23573 2 0.23775 3 0.23775 3 0.23766 4 0.23775 3 0.23465 3 0.23465	5 29,97372 31.39322 31.39322 3 37.24632 3 40.41599 3 40.41599 3 40.41599 3 40.67161 48.3956 51.45326 5 51.45326 5 52.12438 9 51.45326 10 73.00902 12 14.0211 19 13.8141 13 14.3224 12 14.0211 13 14.307 13 14.4307 13 14.4307 14 15.62255 71 15.62255 71 15.62255 71 17.3475 31 18.20426 39 18.2726 39 18.4355 351 18.9589	 -0.03583 -0.030275 -0.02275 -0.03902 -0.03902 -0.03902 -0.03902 -0.03902 -0.03902 -0.03903 -0.03115 -0.0308 W MEAN -0.03594 -0.03791 -0.03791 -0.03944 -0.03944 -0.03791 -0.03954 -0.03791 -0.03954 -0.03791 -0.0394437 -0.03954 -0.03956 -0.03928 -0.04678 -0.04678 -0.04678 	0,474322 0,48637 0,50253 0,49256 0,4931 0,48198 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,46293 0,15569 0,07805 0,07905 0,07905 0,07905 0,07905 0,07905 0,07905 0,07905 0,07905 0,0790	2 26.34113 1 27.74774 3 29.72094 6 31.8869 7 35.46843 7 3.5.46843 7 3.5.46843 9 43.46845 9 43.46863 9 43.46863 9 2.396397 7 5.441385 9 2.396397 7 5.441385 7 5.4	-0.00706 -0.01674 -0.01686 -0.01916 -0.0125 -0.01739 -0.00287 -0.00287 -0.00287 -0.00345 -0.00175 -0.00175 -0.000176 -0.000176 -0.000176 -0.000176 -0.00018 -0.00018 -0.00018 -0.000199 2-0.0052 1-0.0052 1-0.00642 1-0.00642 1-0.00642 1-0.00643 2-0.00352 -0.00352	0.5 0 -0.5 0 -1 -1.5 2 -1.5 2 -1.5 -1.5 -1.5 -	6D downstream velocity profile m/s 2 4 6 8 10 12 14 16 18 Radial (mm)
X 6D dov stream	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1,69085 1,69085 1,69085 1,69085 1,25472 1,39044 1,2530 1,06548 0,93332 0,81839 0,65747 U MEAN 1,43450 2,15428 3,15544 4,156288 5,155659 3,1,5444 1,56288 5,1,55659 3,1,5444 1,56288 5,1,55659 3,1,5444 1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55659 3,1,5444 4,1,56288 5,1,55639 3,1,5444 4,1,37984 4,1,3	0 33973 2 0.5502 3 0.56395 7 0.57536 8 0.56196 0 0.54733 9 0.49728 2 0.45410 2 0.42108 2 0.42108 2 0.42218 9 0.33006 8 0.22875 8 0.21590 1 0.21323 2 0.21323 2 0.21323 1 0.21323 2 0.21403 3 0.22403 3 0.23076 4 0.23676 4 0.2377 9 0.23267 3 0.23267 3 0.23267 3 0.23267 3 0.23267 3 0.23563 3 0.25250	5 29,9737; 31.39322; 33.6491; 3 33.6491; 3 37.2463; 3 40.4159; 3 40.4159; 3 42.6741; 1 46.6716; 7 48.395; 62.1243; UTURBU 0 7.3.0090; 7 13.802; 10 13.814; 17 13.8098; 38 14.307; 19 13.8098; 39 16.4037; 11 15.6225; 12 14.021; 39 13.8098; 38 14.307; 14 8731; 15 6225; 71 17.3475; 31 18.2245; 39 18.432; 39 18.435; 31 18.255; 31 18.255; 31 18.435; 35 18.435; 31 18.5	 -0.03583 -0.03157 -0.02275 -0.02759 -0.03902 -0.04376 -0.05338 -0.01666 -0.01666 -0.03008 J W MEAN -0.03594 -0.03979 -0.03594 -0.03926 -0.03926 -0.03872 -0.03892 -0.03892<	0,474322 0,48637 0,50253 0,49256 0,49256 0,46293 0,46293 0,46293 0,46393 0,46393 0,66293 0,03695 0,03695 0,03695 0,03695 0,00798 0,07805 0,03695 0,00798 0,007805 0,03695 0,00614 0,07890 0,0780000000000	2 26.34113 1 27.74774 3 29.72098 6 31.8869 7 35.46843 7 38.46476 9 43.44845 3 46.25208 9 43.44845 9 43.44845 9 43.44845 9 43.44845 9 43.44845 9 43.96331 9 2.387801 W TURBL 5.441389 9 2.396397 6 5.67122 2 5.1098813 3 10.33752 4 11.21822 1 12.25731 6 12.7510 6 13.4690 67 13.9194 19 15.27722 11 16.3802 33 18.7306 33 18.7306 33 16.3312 74 16.6079	-0.00706 -0.01674 -0.01688 -0.01916 -0.0125 -0.0125 -0.00287 -0.00287 -0.00346 -0.00175 Juw -0.000176 -0.000176 -0.000176 -0.000174 -0.000174 -0.000175 2 -0.00149 2 -0.00199 2 -0.00512 1 -0.00481 5 -0.00481 5 -0.00352 8 -0.00352 8 -0.00352 8 -0.00352	0.5 0 -0.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1 -1 -1.5 -1.5 -	6D downstream velocity profile m/s 6D downstream velocity profile 7 2 4 6 8 10 12 14 16 18 Radial (mm)

SHEAR STRESS AND TURBULENCE INTENSITY IN 2 mm ECCENTRIC BALL OCCLUDER













