THE UNIVERSITY OF ADELAIDE

DEPARTMENT OF MECHANICAL ENGINEERING

ESTABLISHING VERY LOW SPEED, DISTURBANCE-FREE FLOW FOR ANEMOMETRY IN TURBULENT BOUNDARY LAYERS

presented by

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for the Degree of Doctor of Philosophy

December 1997

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Summary

This document addresses problems encountered when establishing the very low air-flow speeds required for experimental investigations of the mechanisms of low-Reynolds-number boundary-layer turbulence. Small-scale motions in the near-wall region are important features of turbulent boundary-layer dynamics, and, if these features are to be resolved by measurements in air with conventionally-sized hot-wire probes, a well-behaved canonical turbulent boundary layer must be developed at free stream flow speeds no higher than 4 m/s. However, at such low speeds, the turbulent boundary layers developed on the walls of a wind tunnel are very susceptible to perturbation by non-turbulent time-dependent flow structures which originate upstream from the test section in the laminar flow at the inlet and in the contraction.

Four different non-turbulent flow structures have been identified. The first is a result of quasi-two-dimensional separation of the laminar boundary-layer from the surfaces of the wind-tunnel contraction. Potential flow simulations show that susceptibility to this form of separation is reduced by increasing the degree of axisymmetry in the cross-section geometry and by decreasing the streamwise curvature of the concave surfaces. The second source of time-dependence in the laminar boundary-layer flow is an array of weak streamwise vortices produced by Görtler instability. The Görtler vortices can be removed by boundary-layer suction at the contraction exit. The third form of flow perturbation, revealed by visualisation experiments with streamers, is a weak large-scale forced-vortex swirl produced by random spatial fluctuations of temperature at the wind-tunnel inlet. This can be prevented by thorough mixing of the inlet flow; for example, a centrifugal blower installed at the inlet reduces the amplitude of temperature nonuniformity by a factor of about forty and so prevents buoyancy-driven swirl. When subjected to weak pressure gradients near the start of a wind-tunnel contraction, Görtler vortices in laminar wall layers can develop into three-dimensional separations with strong counter-rotating trailing vortices. These trailing vortices are the fourth source of unsteady flow in the test-section. They can be suppressed by a series of appropriately located screens which remove the low-speed-streak precursors of the three-dimensional separations. Elimination of the above four contaminating secondary flows permits the development of a steady uniform downstream flow and well-behaved turbulent wall layers.

Measurements of velocity in the turbulent boundary layer of the test-section have been obtained by hot-wire anemometry. When a hot-wire probe is located within the viscous sublayer, heat transfer from the hot-wire filament to the wall produces significant errors in the measurements of both the mean and the fluctuating velocity components. This error is known as wall-proximity effect and two successful methods are developed for removing it from the hot-wire signal. The first method is based on the observation that, if all experimental parameters except flow speed and distance from the wall are fixed, the velocity error may be expressed nondimensionally as a function of only one parameter, in the form $\Delta U^+ = f(y^+)$. The second method, which also accommodates the effect of changing the hot-wire overheat ratio, is based on a dimensional analyis of heat transfer to the wall.

Velocity measurements in the turbulent boundary layer at the mid-plane of a nearly square test-section duct have established that, when the boundary-layer thickness is less than one quarter of the duct height, mean-velocity characteristics are indistinguishable from those of a two-dimensional flat-plate boundary layer. In thicker mid-plane boundary layers, the mean-velocity characteristics are affected by stress-induced secondary flow and by lateral constriction of the boundary-layer wake region. A significant difference between flat-plate and duct boundary layers is also observed in momentum-balance calculations. The momentum-integral equation for a duct requires definitions of momentum and displacement thickness which are different from those given for flat-plate boundary layers. Momentum-thickness growth rates predicted by the momentum-integral equation for a duct agree closely with measurements of the newly defined duct momentum thickness. Such agreement cannot be obtained in terms of standard flat-plate momentum thickness.

In duct boundary layers with Reynolds numbers (Re_{θ_2}) between 400 and 2600, similarity in the wake-region distributions of streamwise turbulence statistics has been obtained by normalising distance from the wall with the flat-plate momentum thickness, θ_2. This result indicates that, in contrast with the mean velocity characteristics, the structure of mid-plane turbulence does not depend on the proportion of duct cross-section occupied by boundary layers and is essentially the same as in a flat-plate boundary layer. For Reynolds numbers less than 400, both wall-region and wake-region similarity fail because near-wall turbulence events interact strongly with the free stream flow and because large scale turbulence motions are directly influenced by the wall. In these conditions, which exist in both duct and flat-plate turbulent boundary layers, there is no distinct near-wall or wake region, and the behaviour of turbulence throughout the boundary layer depends on both wall variables and on outer region variables simultaneously.

Acknowledgments

This project would never have been completed without the assistance of many other people. My most sincere thanks must go to Dr. M. K. Bull for acting as my supervisor and for obtaining financial support from the Australian Research Council. His friendly advice has always been useful and has contributed significantly to the quality of my work. Discussions with Professor R.E. Luxton have been most interesting and are much appreciated. I also thank Drs. G. J. Nathan and R. M. Kelso for instruction on flow topology, for their friendship and for helping me whenever I asked. Drs. C. H. Hansen and J. M. Pickles have provided welcome assistance in negotiating the bureaucratic maze.

The research findings of this project have arisen almost entirely from experimental work and so, in the manufacture and maintenance of equipment, the willing assistance of technicians and tradesmen has been particularly valuable. Most technical staff in the Department of Mechanical Engineering have contributed in some way to my work and to my education. Rod Curtin, Eric Browne, Alan Mittler and Jonathan May have provided vital support for the computer hardware and systems software. Initial low-level graphics software for the Visual 500 display terminal came from Rod. The data acquisition hardware was designed and built by Rod Curtin, Alan Mittler and Silvio DeIeso. Alan and Silvio also designed and assembled much of the analogue instrumentation. George Osborne made the all-important anemometer probes and most of the associated fittings. The workshop staff: Ron Jager, Craig Price, Malcolm Bethune, Dudley Morrison, Doug Smith, Bill Doble and Werner Eidam have manufactured or modified numerous wind-tunnel components for me. Their support and practical advice are highly appreciated. I have particular gratitude for Herwig Bode who, in providing access to innumerable items of equipment and in many other ways, has given absolutely first-class service.

Statement of originality

This work contains no material which has been accepted for the award of any other degree or diploma in any university or 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.

Peter Vernon Lanspeary

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