The effect of density on the near field of a naturally occurring oscillating jet

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Preface

This document is the culmination of many years of study, and is the thesis submitted for the award of Doctoral of Philosophy. The topic of research is the effect that the density ratio has on the near field flow emitted from a nozzle that produces a naturally occurring oscillation. The nozzle investigated know as the Triangular Oscillating Jet (TOJ) is derived from the Fluidic Precessing Jet (FPJ). The FPJ nozzle has shown significant combustion benefits, namely reduced emissions and improved efficiency, when used in cement and lime kilns, particularly with gaseous fuels. Work on the TOJ is helping to extend the same benefits to solid fuel situations. With global climate change increasingly at the forefront of every ones mind it is important to continue to develop highly efficient, low polluting combustion systems. The work presented in this thesis uses a lab scale nozzle under cold flow conditions to examine the effect of varying density ratio, simulating different kiln air temperatures. The intention of this work is to further the understanding of the flow from the TOJ nozzle leading to improved design for combustion systems.

Declarations

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.

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Abstract

A major component of the world's ever increasing energy demand is supplied by combustion. Despite concerns of the enhanced greenhouse effect, primarily due to the emission of CO_2, fossil fuels will remain a major energy source for the foreseeable future. One approach to help to combat the enhanced greenhouse effects of combustion is to design highly efficient burners that achieve low levels of pollution. The fluidic precessing jet (FPJ) and the related triangular oscillating jet (TOJ) burners have shown such benefits when used in the cement and lime industry. As a result, they have been studied at the University of Adelaide for many years. Despite these investigations there are still significant gaps in the understanding of how they work. Addressing these gaps will allow their design to be improved. This work focuses on improving the understanding of the TOJ, and also provides insight into the understanding of the FPJ.

The benefits that can be provided by the FPJ and TOJ nozzles include fuel savings of up to 10% and NO_x reduction between 40-70%. This is due to the flows they produce. These flows are unsteady, creating large scale unique eddies that alter the mixing of the fuel and air, and hence the combustion. Many nozzle parameters, such as the nozzle expansion ratio and chamber length to diameter ratio, influence the nature of these unsteady flows. The influence of such parameters is well understood when the density ratio between the nozzle fluid and the ambient is unity. However, no previous investigations of the effect of density ratio on FPJ or TOJ flows have been performed. Density ratio has been previously shown to alter mixing in simple jets, and will therefore also affect the mixing of an unsteady flow. Therefore an understanding of how the jet-to-ambient fluid density ratio affects the flow from the TOJ is required to further our knowledge and improve its design.

To gain an understanding of the effects of density ratio, the TOJ nozzle has been investigated under cold flow conditions over a broad range of density ratios. Particle image velocimetry (PIV) and oscillation frequency data have been collected to assess any density ratio effects on the near field of the flow emerging from the TOJ nozzle. Along with the oscillation frequency, key flow parameters measured were the mean jet spread, the mean jet decay and the instantaneous jet deflection angle.

The role of density ratio (jet fluid/ambient fluid), and its relative influence is assessed with the nozzle chamber length fixed. The effect of density ratio is also investigated with the chamber length as a variable and in a more industrially relevant configuration, in which a co-annular flow surrounds the TOJ flow.

Although the sensitivity to density ratio is less significant when the density ratio is greater than unity, it was found that increasing the density ratio leads to an increase in the mean spread, decay rate and the instantaneous jet deflection angle, and a decrease in the frequency of oscillation. At any given density ratio, increasing the nozzle chamber length within the investigated range resulted in an increase in the mean spread, decay rate and instantaneous jet deflection angle as well as an increase in the frequency of oscillation. While no measurements of the flow were taken within the nozzle chamber, frequency measurements suggest a decrease in the density ratio is analogous to an increase in the chamber length with respect to the influence on the internal flow.

The results from this study shed new light on the flow in the near field region of the TOJ nozzle. The knowledge gained will allow future designs for industrial use to be better tailored to use in rotary kilns, and contribute to improved efficiency and reduced emissions.

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Notation

Latin

d_0	Nozzle diameter [m]
d_2	Exit lip diameter [m]
d_{e1}	Orifice equivalent diameter [m]
d_p	Particle diameter [m]
D	Chamber diameter [m]
D_j	Jet diameter [m]
f	Frequency response of particles [Hz]
f_{osc}	Frequency of oscillation [Hz]
FPJ	Fluidic precessing jet
Fr	Froude number
g	Acceleration due to gravity [ms^{-2}]
L	Chamber length [m]
M	Momentum [kgms^{-1}]
PIV	Particle image velocimetry
r	Radial distance [m]
$r_{1/2}$	Half width [m]
$\bar{r_{1/2}}$	Mean half width [m]
Re	Reynold's number
S	Density ratio between the jet and ambient
Sk	Stokes number
St_{osc}	Strouhal number of oscillation
TOJ	Triangular oscillating jet
u	Axial velocity [ms^{-1}]
$\bar{U_1}$	Bulk mean velocity [ms^{-1}]
U_c	Mean centreline velocity [ms^{-1}]
x	Axial distance [m]

Greek

Δ	Difference
λ	Wavelength [nm]
ρ	Density [kgm^{-3}]
μ	Dynamic viscosity [kgm^{-1}s^{-1}]
ν	Kinematic viscosity [m^{2}s^{-1}]
σ	Particle to fluid density ratio
θ	Instantaneous jet deflection angle [°]
τ_p	Particle aerodynamic response time
τ_r	Representative flow time scale

Subscripts

a	Ambient
$c-a$	Co-annular flow
j	Jet
TOJ	Triangular oscillating flow
x	Axial
ϕ	Angular