15th Australasian Fluid Mechanics Conference
The University of Sydney, Sydney, Australia
13-17 December 2004

Experimental Investigation of a Rectangular Slot-Burner in the presence of Cross-Flow for different Jet Velocity Ratios

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Abstract

In a typical coal-fired power station boiler the ignition and the combustion are largely controlled by burner aerodynamics, hence the geometry of the burner and the jet velocity ratio play an important role in achieving stable combustion, high burnout of fuel, low production of pollutants and control of fouling. Slot-burners are used in tangentially fired brown coal boilers in Victoria. To obtain a better understanding of the overall combustion process, it is important to investigate the aerodynamics of the jet development from these burners. The aim of this paper is to investigate a rectangular slot burner in the presence of cross flow for jet velocity ratios of 1.0 and 3.0. A simple burner has been considered for investigation where the jets discharge at an angle of 60° to the wall. The burner consists of three rectangular slots vertically aligned with the centre known as primary nozzle and the top and bottom ones known as secondary nozzles. The velocity ratio (ϕ) is defined as the ratio of secondary to primary jet velocity. Laser Doppler Anemometry experiments have been carried out at CSIRO Minerals. In the presence of cross flow, both primary and secondary jets deviated significantly from the geometric axis towards the wall.

Introduction

A jet in cross flow has been the subject of numerous studies because of its wide variety of applications in engineering. Chimney plumes for the dispersion of pollutants in the atmosphere, the cooling of turbine blades, lifting jets for V/STOL aircraft, fuel injection of burners and jets of oil and gas entering the flow in oil wells are just a few important examples. Many researchers have studied a circular jet in cross flow extensively. Foss [6], Andreopoulos [2,3], Andreopoulos and Rodi [4] reported on an extensive investigation of the near field aerodynamics of a round jet issuing normal to the surface and to the cross flow. Catalano *et al.* [5] investigated physically and numerically the development of a system for jet to cross flow velocity ratio equal to 2.0 and 4.0 where the cross flow was confined between two parallel surfaces. Sherif & Pletcher [17] in surveying numerical and physical modelling studies of jets in cross flow, consider that these systems are, generally, more difficult to model numerically than wall boundary-layer flows primarily because of the curvature of the shear layer and the complex turbulent flow pattern in the jet wake region. Sykes *et al.* [19] developed a time marching solution of the incompressible Navier-Stokes equations and discretized them on to a grid using central spatial differencing on a non-uniform grid. The model was used to investigate the details of the flow within the jet in cross flow. Smith and Mungal [18] presented the results from extensive imaging of the concentration field of a jet in cross flow. Lester *et al.* [11] reported on a series of large-eddy simulations of a round jet issuing normally into a cross flow. Simulations were performed at two jet-to-cross flow velocity ratios, 2.0 and 3.3, and two Reynolds numbers, 1050 and 2100, based on cross flow velocity and jet diameter. The mechanisms by which large-scale coherent structures form were described in their investigation. Lim *et al.* [12] also investigated the development of large-scale structures of a jet normal to a cross flow. Peterson and Plesniak [15] studied the evolution of a short injection-hole jet issuing into a cross flow at low blowing ratio by using PIV technique. It is well-established from all of these investigations that a circular jet in cross flow produces a multitude of vortical structures and the five most significant ones are the leading edge vortices, lee-side vortices, counter-rotating vortex pairs, horseshoe vortices and wake vortices.

There are substantially fewer papers dealing with studies of multiple round jets in cross flow compared to those dealing with a single round jet in the same environment. Examples of the papers dealing with multiple round jets include Isaac & Schetz [10], Makihata & Miyai [13], Isaac & Jakubowski [9] and Savory & Toy [16]. Multi-jet configurations studied include two or three jets aligned in a row transverse to the cross flow direction, two jets in tandem and three jets each located at a corner of an equilateral triangle. Velocity ratios between the jets equal one, and between the jet and cross flow range from 2.0 to 10.0. In recent years, various attempts have been made to improve the mixing efficiency of a jet in cross flow by using non-circular jet geometry such as an ellipse, square and rectangle. New *et al.* [14] studied the flow structures of an elliptic jet in cross flow in a water tunnel using laser-induced fluorescence technique and for a range of jet aspect ratio from 0.3 to 3.0. A similar investigation was conducted by Haven & Kurosaka [8] to examine the effect of hole exit geometry on the near field characteristics of cross flow jets. Hole shapes investigated were round, elliptical, square and rectangular. Hart [7] investigated in detail the formation mechanism of large-scale coherent structures of multiple rectangular slot burners without cross flow and for secondary to primary jet velocity ratio of 1.0. The effect of jet velocity ratio for multiple rectangular slot burners was extensively studied by Ahmed *et al.* [1] without cross flow. Yan & Perry [20] first investigated the jet velocity ratio effect for the rectangular slot burners in the presence of cross flow. They studied the flow by visualization and took measurements for mean velocity by Laser Doppler Anemometry (LDA) in the near field region. The flow pattern in a tangentially fired rectangular slot burner is very complex and needs detailed investigation to understand the mean and turbulent statistics in near and far field region of the jets. The current work was undertaken to produce more detailed data on mean flow and turbulent stresses in such a flow.

The development of the flow field in the near burner region is influenced by burner geometry, velocity ratio and complex rotational flow in the tangentially fired furnace. In a simple isolated burner study it is not possible to faithfully model all of these influences, particularly the furnace flow field. The cross flow in this isolated burner investigation is the representation of the burner flow field similar to the tangentially fired furnace.

Description of the Burner Model

A simple burner has been considered for investigation where the jets discharge at an angle of 60° to the wall. The burner consists of three nozzles vertically aligned with the centre known as primary nozzle and the outer two known as upper and lower secondary nozzles. The burner model is a large box (1.85mx1.5mx1.6m) made from a frame of aluminium with perspex walls. The dimensions of the cross section of the primary nozzle and the secondary nozzles (upper and lower) in the cold flow model are (75mm x 58mm) and (75mm x 34mm) respectively. The hydraulic diameter (D_e) and the nozzle spacing were 64mm and 27mm respectively. Upstream of the nozzles, the duct length was 1.2m, to give a more developed velocity profile at the exit of the burner. The dimension of the cross section of the cross flow nozzle was (75mm x 252mm) and the duct length was 1.8m. Figure 1(a) and 1(b) show the dimensions of the flow containment box, primary and secondary nozzles respectively.

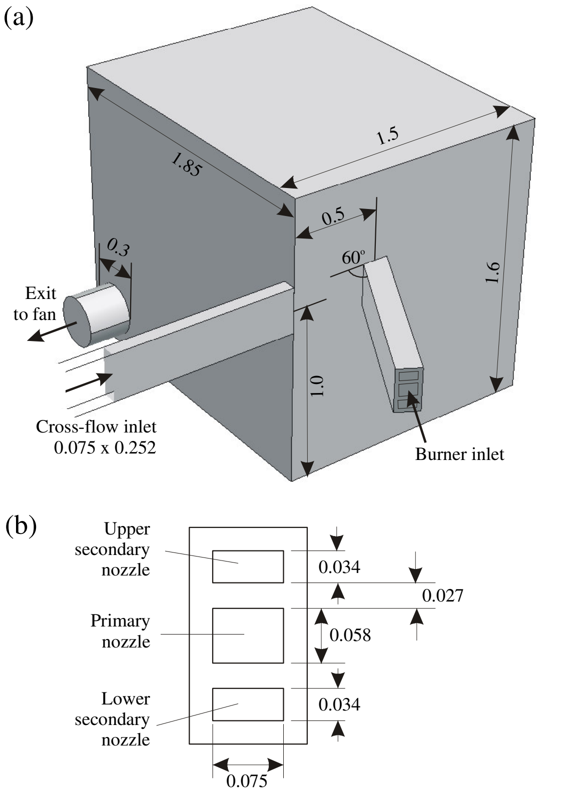

Figure 1. Dimensioned view of flow containment box and burner inlet detail (all units in m)

Experimental Set-up & Measurement Technique

A Schematic diagram of the experimental set up is shown in figure 2. Air passed into the burner model via ducts A (Burner) and B (cross flow), and exited through duct C. It was driven into the rig from the blower and extracted through the bag house using a fan. A 2-axis traversing mechanism was suspended within the enclosure from the roof. This traverse was used to automatically position a laser with high precision. The velocity in the primary jet was held constant at 8m/s. The value of the secondary jet velocity was 8m/s for ϕ=1.0 and 24m/s for ϕ=3.0. The velocity of the cross flow jet was 8m/s and was constant throughout the experiments.

A TSI-Aerometrics 2D Laser Doppler Anemometer (LDA) was used to measure the mean and fluctuating component of velocity. The system consisted of a two-colour four-beam optical arrangement utilising the green (with the wavelength of 514.5 nm) and blue (with wavelength of 488 nm) lines of a 5W Argon-Ion laser. A fibre optic probe had a lens of a 250 mm focal length and a 40 mm beam separation which produced an ellipsoid shaped measuring volume with dimensions of 0.11 mm × 0.11 mm × 1.5 mm. A specially designed 2D traversing mechanism was used inside the containment box to traverse the fibre optic probe.

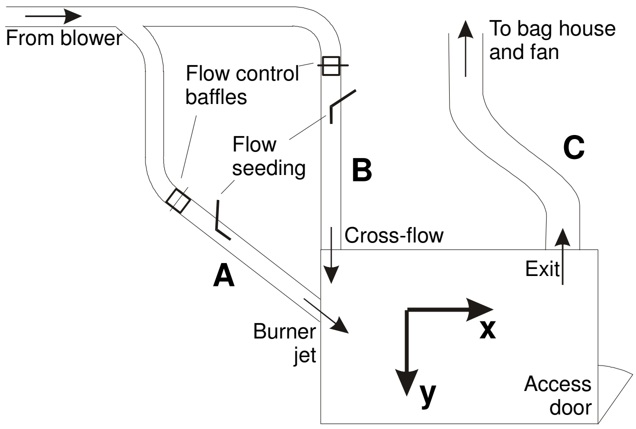

Figure 2. Schematic Diagram of Burner Model and associated ducting

The airflow was seeded with a fine mist of sugar particles introduced into the primary, secondary and cross flow jets. The partially dried sugar particles with a mean diameter about 1 µm were generated by a TSI six-jet Atomizer from a 5% sugar solution. For each position inside the burner model, data was taken for 60 seconds. The average data rate was 400 Hz giving a total of around 24,000 particles counted at each position.

Results and Discussion

Figures 3(a) and 3(b) show the velocity vectors for ϕ= 1.0 at the centre of the primary nozzle (z/De=0) and lower secondary nozzle (z/De=1.14) respectively.

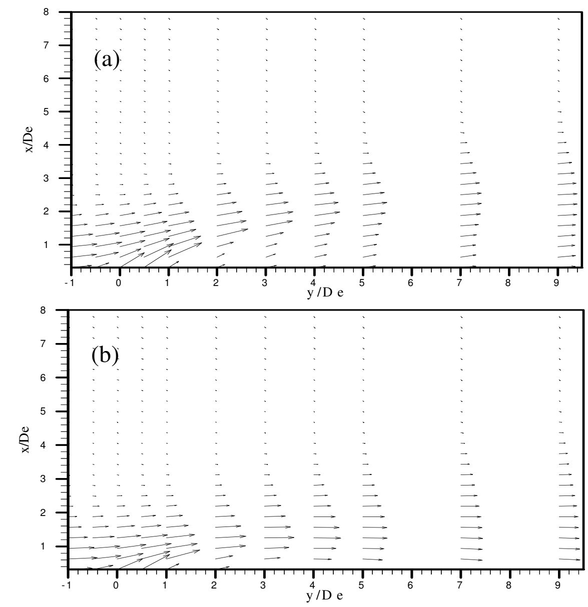

Figure 3(a-b). Velocity vectors at the centre of the primary (a) and lower secondary (b) nozzles for ϕ= 1.0

The direction of the cross flow jet was in the same direction as the component of the jet velocity parallel to the furnace wall. The cross flow has a profound effect on the developing flow field. For this geometry without cross flow, [7] the three jets were aligned almost along the geometric axis of the burner. In the presence of cross flow, the three jets were pushed towards the wall and remained predominantly within the cross flow. The deflection of the lower secondary jet was slightly greater than the primary jet as shown in figure 3(a) and 3(b). The centreline of the primary and lower secondary jet diverged significantly from the geometric axis towards the wall. Figures 4(a) and 4(b) show the velocity vectors for ϕ= 3.0 in the same planes as figure 3.

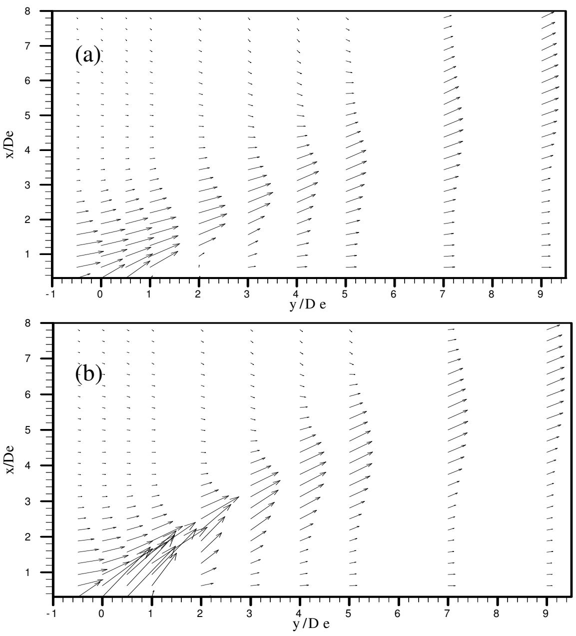

Figure 4(a-b). Velocity vectors at the centre of the primary (a) and lower secondary (b) nozzles for ϕ= 3.0

The flow field changed significantly with the increase in jet velocity ratio. The degree of deflection of primary jet towards the wall was reduced which is clear from figure 4(a). The primary jet penetrated through the cross flow layer whereas it was almost entirely within the cross flow for ϕ=1.0. Due to the mixing of the secondary jets with the primary jet, the momentum of the primary jet was increased allowing the penetration of the primary jet through the cross flow. This phenomenon can be understood more clearly in figure 4(b) where the deflection of the lower secondary jet was minor from the geometric axis due to its high momentum showing that the jet pierced the cross flow layer.

Comparisons of the resultant velocity (U) at the centre of the primary nozzle are presented in figures 6(a-b) for a number of lines downstream of the primary jet. The lines are y/De=0, 1, 3, 5 and 9. The velocities were measured in two perpendicular directions with u normal and v parallel to the cross-flow. All velocities are normalized to the velocity at the exit of the primary nozzle (x/De=0, y/De=0, z/De=0). Measurement lines are shown in figure 5.

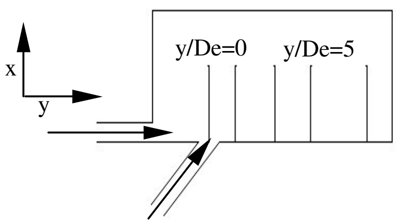

Figure 5. Schematic diagram showing the measurement lines

At y/De=0, the peak values are at the exit of the nozzle for both jet velocity ratios. At y/De=1, although the peak values occurred at the same position (x/De=0.8) for both jet velocity ratios, the spreading of the jet for ϕ=3.0 is greater than for ϕ=1.0. Further downstream (y/De=3, 5 and 9), the peak value for ϕ=3.0 shifted farther from the wall than ϕ=1.0 and the difference is clear at y/De=5 where the peak value for ϕ=1.0 is at around x/De=2.2 and for ϕ=3.0 is at x/De=3.8. At y/De=9 the difference between the peak values is at a maximum. This clearly indicates more spreading of the primary jet and less deviation from the geometric axis for ϕ=3.0.

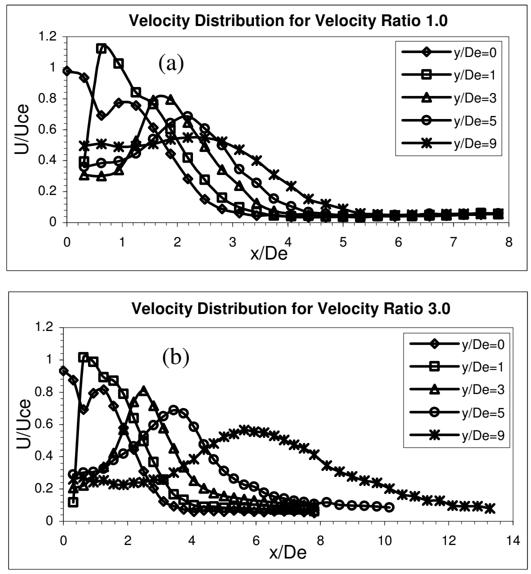

Figure 6(a-b). Velocity distribution at the centre of the primary nozzle for jet velocity ratio 1.0 (a) and 3.0 (b)

Figure 7(a-b) shows u_{rms} at the centre of the primary nozzle for jet velocity ratios of 1.0 and 3.0 respectively. At y/De=0, for ϕ=1.0, very near to the wall (x/De=0.31), there is a non-zero value (0.06) of u_{rms}. This non-zero value occurred due to diffusion transport in the cross-stream directions from regions of peak generation. After that there is a sudden peak of u_{rms} due to interaction between the primary jet and the cross flow. The magnitude then fell, gradually increased and reached the second peak at x/De=2.0. At y/De=1, peak value occurred at x/De=0.31 because of the generation of turbulence due to high velocity gradient.

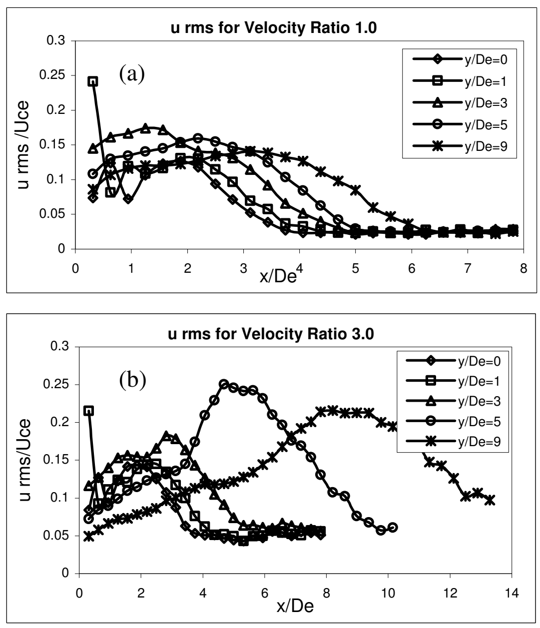

Figure 7(a-b). Comparison of u rms at the centre of the primary nozzle for jet velocity ratio 1.0 (a) and 3.0 (b)

In this region there was a reverse flow. Further downstream (y/De=3, 5 and 9) the peak values of u rms shifted and occurred at the centreline of the jet. The peak values at this region occurred because of the diffusive redistribution of the normal stresses from the cross-stream generation regions. The trend is similar for ϕ=3.0 at y/De=0 and 1 but the magnitude of the peak values at y/De=3, 5 and 9 are higher than those in ϕ=1.0. Figure 8(a-b) shows the v_{rms} at the same planes for ϕ=1.0 and 3.0 respectively. Unlike the u_{rms}, there is only one peak at y/De=0 both for ϕ=1.0 and ϕ=3.0. At y/De=1, the peak value occurred near to the wall (x/De=0.31) because of high velocity gradient as mentioned earlier. Further downstream the peak values shifted and occurred at the centreline of the jet due to the diffusive redistribution from the cross-stream generation regions.

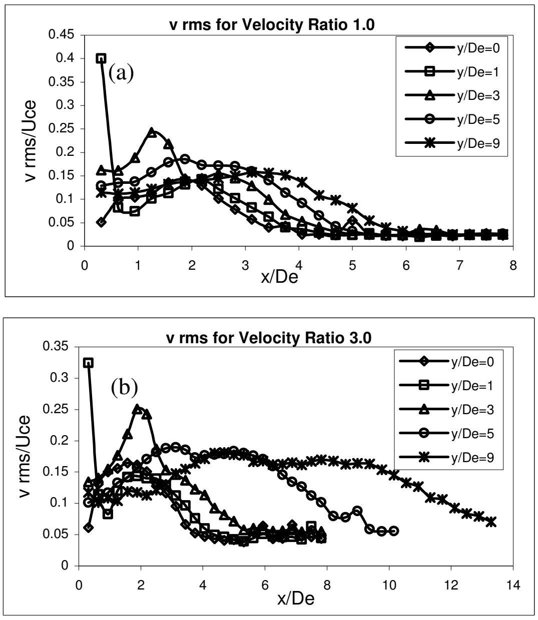

Figure 8(a-b). Comparison of v rms at the centre of the primary nozzle for jet velocity ratio 1.0 (a) and 3.0 (b)

Conclusions

The effect of jet velocity ratio on jet development in the presence of cross flow has been investigated in this paper. The burner was at an angle of 60° to the wall. The experiment was conducted for jet velocity ratios of 1.0 and 3.0. The LDA technique was used to measure the mean velocity component and turbulent fluctuation. Cross flow had a significant effect in developing the near field region. In the presence of cross flow both the primary jet and the secondary jet deviated from the geometric axis towards the wall and remained within the cross flow for velocity ratio 1.0. For ϕ=3.0, the primary jet penetrated the cross flow layer due to higher momentum of the secondary jets. The deviation of the jet centreline from the geometric axis was less for ϕ=3.0. The spreading of the jets for ϕ=3.0 was more than for ϕ=1.0. There were two peaks for u_{rms} at y/De=0 both for jet velocity ratios of 1.0 and 3.0. At y/De=1, near to the wall (x/De=0.3), u_{rms} was high because of high velocity gradient. This investigation of the effect of jet velocity ratio indicates that simple small-scale isothermal models can be a major aid in the interpretation of observations in more complex flow environments.

Acknowledgments

The authors gratefully acknowledge the financial and other support received for this research from the Cooperative Research Centre (CRC) for Clean Power from Lignite, which is established and supported under the Australian Government's Cooperative Research Centres program.

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