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THE INFLUENCE OF NOZZLE GEOMETRY ON THE DEVELOPMENT OF A THREE-JET ISOTHERMAL FLOW FIELD

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SUMMARY. To obtain an improved understanding of the combustion and heat transfer processes in brown coal-fired boilers further information is required on the fluid dynamic characteristics of burners and furnaces. This report presents the results of an experimental investigation of the aerodynamics of slot burners. A number of realistic burner geometries have been characterised with experimental data covering a wide range of jet velocity ratios and including flow visualisation observations, transverse velocity profile and surface static pressure measurements. The problem of measuring velocity and static pressure in confined complex flows is considered. The experiments have shown that burner geometry and secondary to primary jet velocity ratio may significantly influence jet development. Concurrently a mathematical model of the jet flow field is under development and both these programs are continuing.

INTRODUCTION

Victoria's Latrobe Valley brown coal deposit is unique due, in part, to its high moisture content of 55% to 65%. To minimise furnace fouling and pollutant production and to ensure optimum combustion stability and efficiency when burning this fuel it is necessary to obtain an improved understanding of the relevant combustion and heat transfer processes. To achieve this objective the Commission has undertaken an integrated program of mathematical modelling and experimentation including mathematical models of the ignition, combustion and heat transfer processes in a boiler (Johnson and Juniper (1979)); full scale plant measurements (Juniper, (1973), Byrne and Juniper (1983), Ellul et al (1983)); and isothermal model studies to characterise fluid dynamic processes in burners and furnaces (Perry 1982, Perry and Hausler (1983)).

In general, combustion in a coal fired power station boiler can be divided into two regions: ignition and early combustion of the pulverised fuel which is controlled by the burner, and overall combustion and heat transfer which is controlled by the furnace environment. This program considers the aerodynamics of the burner controlled phase in the combustion process.

Current practice in burner design is to use either swirl burners or tangentially fired slot burners. Although the latter system has been adopted for coal-fired power station boilers in Victoria, a comprehensive study of the operation and basis for optimisation of slot burners for tangentially fired boilers is yet to appear in the open literature.

In 1981 a research program was initiated to investigate the aerodynamics of the slot burner system. A review of the available literature (Perry (1982)) revealed little information directly relevant to the rectangular jets of interest and as a result an experimental program was undertaken to investigate the influence of primary to secondary jet velocity ratio, burner geometry, burner exit velocity profile and fuel particles in the primary stream on the near field jet development in an isothermal model. It was quickly appreciated that a mathematical model of the slot burner system should be developed. Such a model would assist in understanding the complex mixing processes between the three jets and reduce the number of burner geometries requiring experimental modelling. The ultimate aim is to integrate these experimental and modelling studies with parallel work on ignition and heat transfer to produce a complete combustion model.

This paper presents the more significant results obtained from the experimental program to date.

EXPERIMENTAL PROGRAM

Stable combustion is achieved in the tangentially-fired boiler by orientating the burner jets so as to induce a vortex in the central region of the boiler. To achieve this in a furnace of rectangular cross-section the burner axis is inclined to the furnace wall and the burner exit plane is indented into the furnace wall. Out-of-service burners are protected from overheating by using cooling air bleed and recessing the burner face into the furnace wall. A slot burner may consist of a central (primary) slot injecting a fuel/gas mixture with secondary air slots located above and below. There is significant separation between slots.

Burner design parameters can vary significantly between boiler manufacturers. These include slot aspect ratio and spacing, secondary to primary jet velocity ratio, the angle of the jets in relation to each other and the geometry and depth of the burner recess.

The experimental program has been designed to assess the influence of these aerodynamic and geometric variables on the near field development of an isothermal, three-jet flow system. The following geometries have been tested:

Geometry 'A' (Figure 1) - A three jet burner where the burner face is located at the boiler wall and the jet exit flow direction is normal to this wall. This arrangement was also used to investigate the flow development from a single jet, with the two side jets blocked at the exit plane.

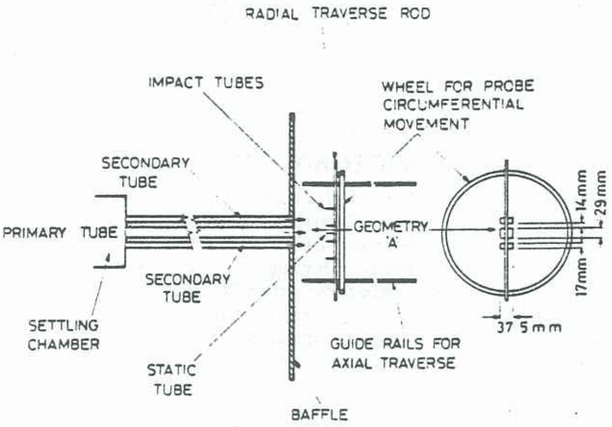


FIGURE 1 : Slot burner model with Geometry A

Geometry 'B' (Figure 2) - As for Geometry 'A' but with the jet flow direction set at 60° to the boiler wall.

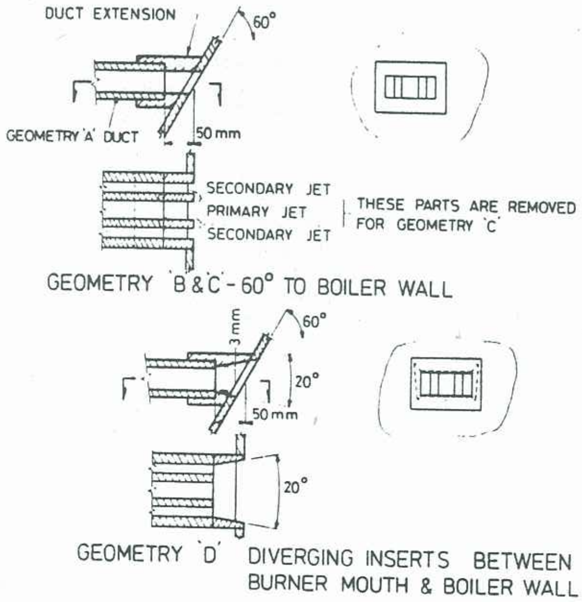


FIGURE 2 : Inclined jet configuration - Geometry 'B', 'C' and 'D'

Geometry 'C' (Figure 2) - As for Geometry 'B' but with the dividing walls between the three slots terminated a short distance upstream of the boiler wall.

Geometry 'D' (Figure 2) - Similar to Geometry 'C' but with diverging side and endwalls bounding the flow between the burner exit plane and the boiler wall.

Published experimental studies of single and multi-jet development have concluded that the jet development appears insensitive to velocity for Reynolds number greater than 2.5×10^4. However, these studies have not considered the effect of unequal jet ratios or multi-jet development in recesses similar to the geometries of interest here.

Based on this Reynolds number limit and the airflow and geometric constraints within the laboratory, an experimental facility was designed where primary and secondary slot dimensions were 1/27 the scale of a main burner at the Yallourn W Power Station Stage 1 main burner. Nozzle dimensions were as follows:

	PRIMARY	SECONDARY
Slot width	37.4 mm	37.4 mm
Slot height	29.0 mm	17.4 mm
Maximum Flow Reynolds Number (based on slot hydraulic diameter)	1.3×10^5	9.3×10^4
Base height separating the slots	14 mm	

The model burner and probe traverse system used to measure the jet development is shown schematically on Figure 1. The experimental rig comprises a centrifugal fan with settling chamber and ducts, supplying individual jets, attached downstream of the fan. The supply ducts maintain the cross-section of the nozzle exit plane over a length 52 times the hydraulic diameter of the centre duct. These dimensions were chosen to ensure fully developed flow at the exit plane; providing a reproducable velocity profile at the burner exit plane for all geometries tested and allow comparison with published experimental data of single jet development. The velocity ratio between the jets could be varied by positioning screens of suitable blockage ratio just downstream of the duct inlet.

The probe traverse system was designed with three degrees of freedom, movement along the geometric axis of the jet, rotation about the jet axis and radial movement perpendicular to this axis. The traverse system was carefully set up to ensure that the axis of rotation coincided with the geometric axis of the jet.

The mean velocity levels within the jet flows were derived from impact/static pressure and hot wire anemometer measurements. Static pressures were obtained from either wall static tappings or a 'half-round nose' static probe. The level of turbulence at the burner outlet plane was measured using a hot wire anemometer. Flow visualisation observations were made with smoke tracers and tufted wands.

The static probe accuracy was checked by comparison with a reference Pitot/static tube in a wind tunnel. For mean flow measurements the hot wire probe was calibrated, before and after each traverse, in the centre of the primary jet flow at the burner outlet plane.

RESULTS AND DISCUSSION

Detailed measurements have been made of the jet flow development downstream of nozzle geometries A, B, C and D covering the region between the burner exit plane and a point nine hydraulic diameters, (d), of the primary jet in the axial direction. These measurements included flow visualisation observations, turbulence measurements at the outlet plane of the burner, decay of axial velocity with axial distance in the centre of the primary jet and of axial velocity on planes normal to the jet axis at a number of axial positions in the flow.

In the figures referred to in the following discussion the symbol lamda (λ) represents the ratio between secondary and primary jet velocities. In the isothermal tests λ^2 is the momentum flux ratio between the jets.

Published experimental studies of jet flow development (Perry (1982)) include many observations of co-axial, round two-jet systems where a relatively thick unvented base region separates the two jets. Due to the co-axial nature of the jets only the outer jet can entrain fluid directly from the surroundings. For a finite base thickness between the two jets, the jet entrainment characteristics induce a low static pressure and recirculation vortices in the base region between jets together with a degree of vortex shedding. This low pressure tends to draw the two jets together and increased mixing between the two jets is induced by the flow recirculation and vortex shedding.

In contrast, due to the characteristic shape of slot burners, the base region between slots may be vented to the surroundings. Observations from flow visualisation suggest that the geometry can significantly influence the mixing and entrainment characteristics of the jets. For Geometry 'A', ambient fluid is entrained around the perimeter of all three jets. Of particular note is the significant degree of entrainment into the base region between jets. Here the entrained fluid would appear to concentrate into regions just above and below the centre of the base region, suggesting that a complex mixing pattern occurs between the jets and entrained fluid in this region.

Entrainment characteristics for Geometry 'B' are similar to that observed for Geometry 'A' except that with the angled wall the lower side dominates entrainment with fluid from this side penetrating 75% of the distance across the base region between the jets.

For jet development in Geometry 'C' and for a momentum flux ratio between 1.0 and 2.0, the three jets meet within the burner recess at a distance 0.5 to 1.0 primary jet hydraulic diameters downstream of the burner exit (Figure 3). The jets completely fill the cavity by the time they reach the furnace wall such that no external entrainment can occur into the cavity or into the base region between jets. As the primary jet velocity is further reduced to a momentum flux ratio of 9.6, the primary jet separates from the lower or short cavity wall. The separation point appears to be located half way along the cavity wall and strong fluid entrainment occurs into the lower side of the primary jet downstream of this point. There does not appear to be any noticeable fluid entrainment into the base region between jcts. The thickness of this separation region increases with increasing momentum flux ratio.

For a momentum flux ratio between 50 and 86 the primary jet appears to split with each half entrained into its neighbouring secondary jet. The flow on the centre plane of the primary jet appears very unsteady.

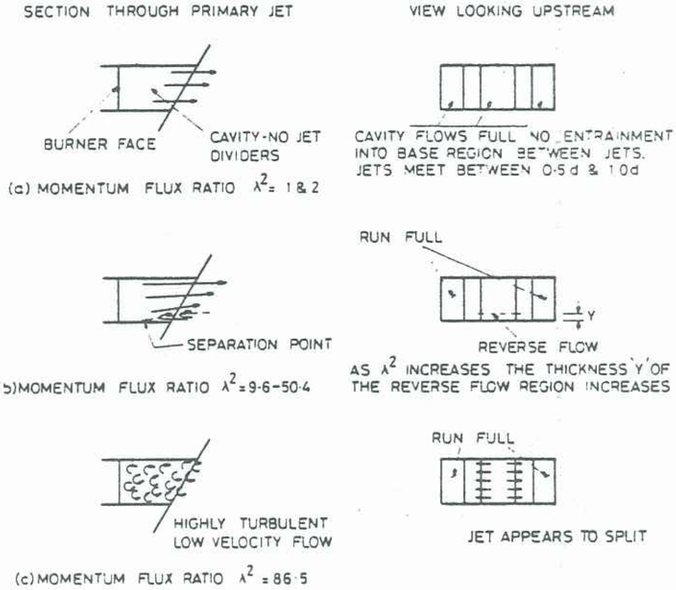


FIGURE 3 : Observations from flow visualisation Geometry C

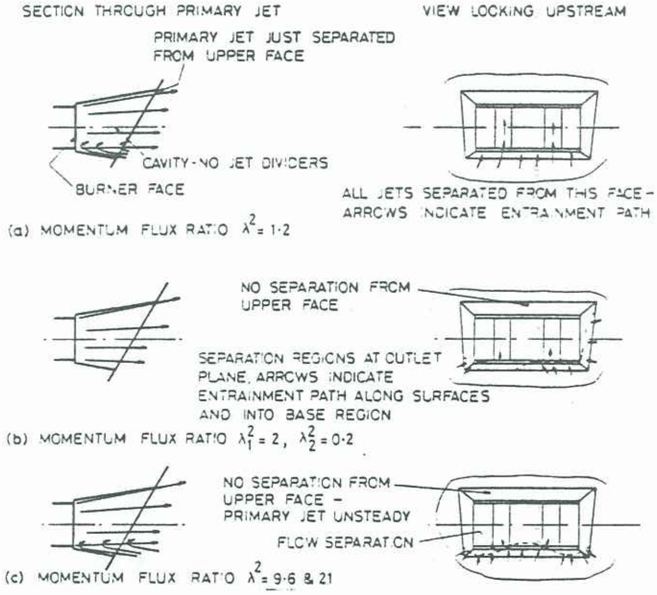


FIGURE 4 : Observations from flow visualisation Geometry D

Compared to the previous three geometries, flow development in the Geometry 'D' cavity is more complex (Figure 4). For momentum flux ratios between 1 and 2 all three jets are separated from the lower, short face with the secondary jets attached to the side and upper faces. The primary jet is separated from the upper face but, with the flow visualisation techniques used, this separation is not always obvious at unity momentum flux ratio. Fluid is entrained from the surroundings into the separated regions and into the base region between the jets. Also, the separation regions across the steps at the burner face can act as a path for fluid movement into the base region from higher pressure regions. The jet flow deflects upward towards the long face and away from the geometric axis of the burner system. For non-equal velocities in the secondary jets represented in Figure 4 by momentum flux ratios of 2 and 0.2, all jets are attached to the upper face of the cavity but the secondary jet with the lowest velocity separated from most of the sidewall and the lower wall. For equal secondary jet velocities, as the primary jet velocity is reduced from a momentum flux ratio of 2 to 9.6, the primary jet attaches to the upper face. As the momentum flux ratio increases from 9.6 to 21 the region of separation appears to reduce in thickness for the secondary and increase for the primary jet. As the momentum flux ratio approaches 50 the primary jet appears to separate again from the upper wall and by 86 the primary jet appears to have split with highly unsteady flow present in this region. Jet splitting occurs at lower momentum flux ratio than in Geometry 'C', possibly due to the effect of the diffusing side and endwalls in Geometry 'D'.

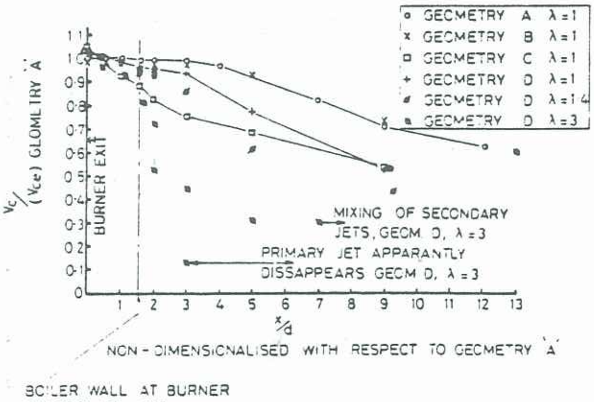
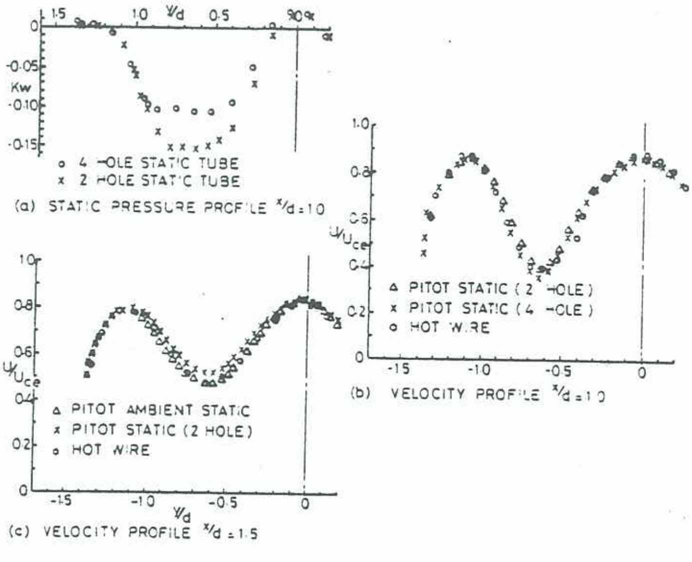


FIGURE 5 : Decay of Peak Axial Velocity

The decay of peak velocity with axial distance in the primary jet is shown on Figure 5. In all cases the axial distance (x) is measured from the burner exit plane and peak velocity is non-dimensionalised with respect to the primary jet centreline velocity at burner exit for Geometry 'A'. For equal primary and secondary jet velocities the axial decay rate of velocity in the primary jet is similar for Geometries 'A' and 'B'. For Geometry 'C', the initial velocity is significantly higher due to the low static pressure at the burner mouth but the decay rate of velocity is much more rapid. Initially this decay is due to flow divergence within and close to the cavity resulting from expansion in both primary and secondary jets to fill the cavity. Further downstream the decay occurs due to entrainment into the primary jet from its surroundings as in the case of Geometries 'A' and 'B'. For Geometry 'D', the initial decay rate in the primary jet is much slower than that observed for Geometry 'C' due to the reduced cavity diffusion rate. Further downstream the jet diffuses rapidly to reach a similar velocity to 'C' by a distance equivalent to nine hydraulic diameters of the primary jet. It was observed from the flow visualisation study that 'C' and 'D' type cavities can produce much greater unsteadiness in the flow than experienced in Geometry 'A'. This could produce an increased level of entrainment into the jet and explain the rapid decay experienced for Geometry 'D'.

Increasing secondary to primary jet velocity ratio (λ = 1 to 1.4) has little influence on the primary jet decay rate for Geometry 'A' (Perry and Hausler (1983)) but significantly increases primary jet decay rate for Geometry 'D' (Figure 5). In this latter case, for λ = 3, the primary jet appears to disappear by about x/d = 6 and the increase in velocity downstream of this point is due to mixing between the two secondary jets.

For burner Geometries 'A', 'B' and 'C', the centreline of the primary jet is close to the geometric axis of the burner. In Geometry 'D' due to non-symmetric flow separation in the cavity, the jets diverge rapidly away from the burner axis with deviation /d = 0.4 for x/d = 5 and λ = 1. For this geometry and λ = 3, the primary jet appears to sit on top of the secondary jet, i.e. it is squeezed upwards.



(a) STATIC PRESSURE PROFILE x/d = 1.0

(b) VELOCITY PROFILE x/d = 1.0

(c) VELOCITY PROFILE x/d = 1.5

FIGURE 6 : Comparison of velocity and static pressure measurement systems - Horizontal traverse through geometric centre of jets : Geometry 'C', λ = 1

The problems of measuring static pressure within, and just downstream of the Geometry 'C' cavity is considered in some detail in Perry and Hausler (1983). Figure 6 shows some of the relevant results where the axial velocity is non-dimensionalised with respect to the maximum velocity in the primary jet at the exit plane. The horizontal axis shows the transverse distance from the geometric axis of the jet and K_w is the ratio of the difference between measured static pressure and ambient pressure divided by the dynamic pressure in the primary duct. Figure 6a compares measurements of static pressure within the cavity using two static pressure probe geometries where the holes on the 'two-hole' static probe were aligned normal to the shear gradient in the mixing layers between jets crossed by the traverse plane. Away from the shear layers the results from the two probes correlated well with each other and with wall static pressure measurements; whereas within the shear layer there are significant differences.

Figure 6b compares velocities within the cavity, derived from combining impact probe and the above static pressure probe measurements and others derived from hot wire measurements. The level of correlation between methods is not good and Perry and Hausler (1983) conclude that for velocity measurement within the cavity no method is totally accurate with the impact probe/ 'two hole' static appearing the most representative. Figure 6c compares velocities derived from these measurement techniques for a horizontal traverse of the flow at the cavity outlet plane. Good agreement is observed between velocities derived from the hot wire probe and the impact probe combined with ambient static pressure. These results indicate that downstream of the exit plane the static pressure within the mixing layer is equal to ambient and that the static probe would appear to be sensitive to velocity shear gradient and fluid mixing.

Similar problems in reliably measuring static pressure were experienced with Geometry 'D'. As noted earlier, the flow within and downstream of the cavity appeared very unsteady and the jets deviated away from the geometric axis. Static pressure probe measurements in mixing layers downstream of the cavity showed pressures significantly less than ambient, particularly for $\lambda = 3$. The difference between velocities in the jet derived from using either ambient or probe static is indicated by the range of uncertainty in the decay of peak velocity in the primary jet for $\lambda = 3$ (Figure 5).

CONCLUSIONS

The experiments have shown that -

- burner geometry can significantly influence the jet development;
- whilst velocity ratio between primary and secondary jets does not significantly influence jet development when the jets discharge at the furnace wall it can have a significant influence with a recessed jet exit;
- small modifications in burner geometry may significantly change the level and position of ambient fluid entrainment into the jet.

The results imply that the burner geometry and velocity ratio are design variables that are available be used to optimise combustion with respect to stability, pollutant formation and furnace fouling.

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