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Coherent Structure Dynamics in Jets from Irregular Shaped Nozzles

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Abstract

Computational Fluid Dynamics was used to model spatially developing, initially laminar, gas jets issuing from nozzles of regular and irregular cross-section, using the Large Eddy Simulation (LES) technique. Nozzles were based on bluff jets used in tangentially fired lignite-burning furnaces. Validation of the LES based model was achieved by comparing predicted jet entrainment rates with published experimental and numerical data. Large-scale coherent turbulent structures including ring and braid vortices and other stream wise structures are predicted by the LES model. The shape of the ring vortices formed was found to directly relate to the nozzle geometry. Size and proximity of discontinuities in the vortex rings were observed to determine how strongly a vortex ring deforms, furthermore discontinuities in the ring curvature were found to alter the number of stream wise structures formed. Jets with only a single pair of braid vortices per side were predicted to spread along their axes while those with multiple braids spread more uniformly.

Introduction

Bluff (rectangular) jets have numerous applications, from low heat-signature jet engines to slot burners in lignite-fired boilers. The entrainment and spreading characteristics of bluff jets are considerably different to those from circular nozzles, due largely to the dynamics of the coherent structures that develop from the nozzle [5]. Bluff jets entrain more fluid and spread more rapidly than circular jets because vortex rings from rectangular nozzles deform more rapidly and to a greater extent than rings from circular nozzles. Coherent structures deform according to (1), the equation for self-induced velocity, $\boldsymbol{u}$, of a vortex ring, [1]

$$u \propto Cb\log\left(\sigma^{-1}\right) \quad (1)$$

where **C** is the local curvature of the ring, **b** is the binormal to the plane containing the ring and $\boldsymbol{\sigma}$ is the local vortex ring thickness or cross-section. Circular rings have uniform curvature resulting in a uniform self-induced velocity according to (1) and are therefore quite stable. Rectangular rings contain large differences in curvature between the straight edges and corner regions; the self-induced velocity of the vortex ring is not uniform, leading to increased deformation [5].

Controlled combustion of coal is highly desirable in tangentially fired boilers in order to provide uniform and predictable heat release. Entrainment characteristics determine how well the fuel-laden primary jet is heated by the hot combustion products within the boiler and also how well it mixes with air from co-flowing secondary-air jets. Tangentially-fired boilers are designed such that most of the combustion occurs within a fireball at the centre of the furnace. The near-field entrainment characteristics must be controlled to prevent early combustion and to conserve sufficient momentum for the jet to reach the centre.

The use of coherent structures as a means of controlling shear flows by selective suppression or augmentation of turbulence is discussed in [10]. One possible method of passive control put forward is and alteration to the initial conditions of the shear flow such as altered velocity profiles. The use of intrusive tabs at the nozzle exit to introduce extra turbulence has been used to increase mixing of rectangular jets with their surroundings [2]. The high rates of wear caused by coal particles make this impractical in coal-burner nozzles. This paper proposes that by combining the properties of circular and rectangular jets the mixing characteristics may be altered, and these characteristics might then be used to selectively enhance or suppress mixing and spreading rates. In order to investigate this, coherent structure dynamics were modelled in jets that are geometrically and hydrodynamically similar to burner jets, with novel semi-circular, semi-rectangular nozzles, hereafter referred to as hybrid nozzles.

Numerical Methods and Boundary Conditions

Two aspect ratio (AR) rectangular nozzles (PRI/SEC), one circular nozzle (CIRC) and one hybrid nozzle (HYB) are presented here. The two rectangular nozzles were similar to typical primary and secondary jet nozzles in a slot burner. The HYB nozzle was essentially the PRI nozzle but the radius of curvature of the corners on one side was half the nozzle's height.

The same mesh was used for each nozzle, with different top-hat velocity profiles imposed on the mesh boundary. The peak mean velocity was 60 m/s and the thickness, δ_o, of the linear shear layer was four mesh elements in all cases. The rectangular corner regions of the nozzle were slightly rounded to ensure a uniform initial vorticity thickness, σ, in (1). To facilitate the roll-up of the shear layer into coherent structures the inlet velocity was perturbed according to a sine function whose frequency resulted in the Strouhal numbers, $St_\delta = f\delta/U$, shown in table 1, which were within the range of preferred natural jet frequencies of these jets. The table compares some hydrodynamic properties of these and other jets from the literature, which were used for validation. Reynolds number was based on the nozzle hydraulic diameter, D.

Run	AR	Re	$St_{\delta o}$	D/δ_0	M
PRI	1.2	270,000	0.041	10	0.17
PRI2	1.2	270,000	0.0496	10	0.17
SEC	2.2	205,000	0.041	7	0.17
CIRC	1.0	139,000	0.041	8	0.17
HYB	1.2	250,000	0.041	9	0.17
SQ1	1.0	>85,000	0.043	11	0.3
SQ3	1.0	>85,000	0.043	11	0.6
SQ4	1.0	>120,000	0.027	16	0.6

Table 1: Hydrodynamic Properties of Jets.

Jets were modelled using a Large Eddy Simulation model based on that of [15], with the Smagorinsky constant, C_S, set to 0.1. A finite-volume coupled solver, CFX5.7, was used to solve the equations on an unstructured mesh containing a mixture of hexahedral and tetrahedral elements. Temporal discretisation was achieved using second-order backward-Euler time-differencing. Spatial discretisation used the quadratic the third-order QUICK differencing scheme. The chosen time step resulted in a Courant flow number of 4, which was found to be stable.

Results

In order to validate the LES model and to provide a source of comparison for the hybrid jet simulations, PRI, PRI2 and SEC were compared with [5] and [7]. Time-averaged statistics were collected for 36 forcing periods of the inlet velocity perturbation, beginning after 4 initial periods. Figure 1 shows the mass flux in the jet, Q, normalized to the mass flux at the nozzle, Q_0, for each simulation and for the experimentally measured mass flux in square, circular and elliptic jets as well as the square jet simulations of [5], who averaged over only eight forcing periods.

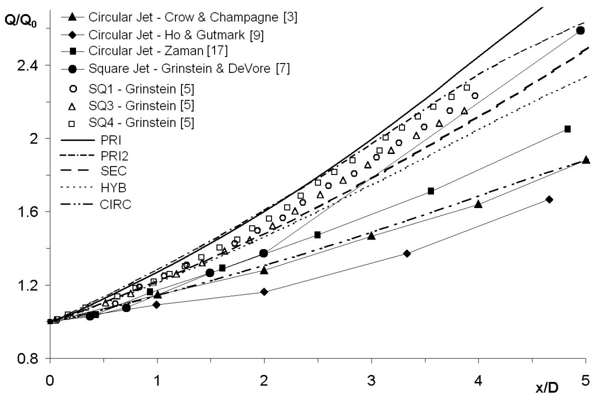

Figure 1: Comparison of Entrainment Rates with Literature.

The entrainment rate (slope of curve) for PRI and PRI2 was very close to the square jets of [5], although slightly higher. The domain modelled here was slightly smaller than in [5], and [6] showed that for a larger computational domain the measured entrainment tends to be reduced, due to an increased contribution from reverse flow in the outer jet region. Figure 1 shows how the rate of entrainment increased in PRI, PRI2 and SEC downstream of the nozzle. For SEC the increase in aspect ratio reduced the entrainment rate, in agreement with [6] for rectangular jets and [14] for elliptic jets. Entrainment rates for circular jets are lower than for rectangular jets of any aspect ratio, and are relatively constant. The entrainment rate of CIRC was within the range of circular jets in the literature.

Separate entrainment curves for the circular side, the rectangular side and the total entrainment in HYB are shown in figure 2. The entrainment was similar to SEC, even though the aspect ratio was the same as PRI. Entrainment by the circular side was significantly higher than in the circular jet of the same diameter. In addition the rate of entrainment was not constant but in fact reduced after three nozzle diameters. Entrainment on the rectangular side was initially very similar to the circular side, although marginally less, but at around three diameters the rate increased and the two curves crossed over. At around four diameters the circular side showed a marked drop in entrainment rate with a corresponding increase on the rectangular side.

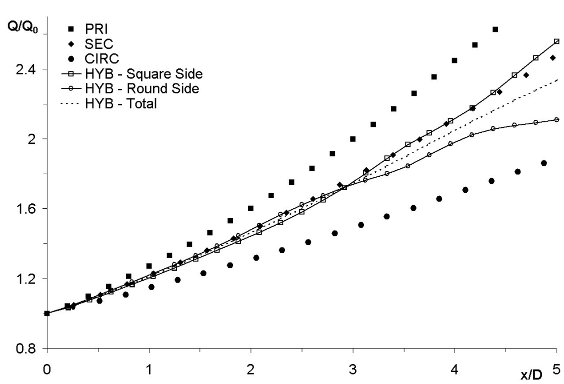

Figure 2: Entrainment Rates for Simulated Jets.

The preceding illustrates how the shape of the nozzle has a large influence on jet entrainment, especially in the near field. What follows is an explanation of this phenomenon by describing the dynamics of the large-scale turbulent structures as they develop within the jet shear layer.

After [11], the black hashed surfaces in figure 3 show regions where the pressure is lower than $^2/_3p_{min}$ and indicate the structure of the vortex rings clearly, while the grey shows isosurfaces of 40% of peak vorticity and indicates the larger turbulent eddies, including vortex rings. The frames cover one full period of oscillation of the inlet velocity. The rings deformed in a manner very similar to the square and rectangular jet simulations of [5], [6] and [7]. The corner regions of the initially planar ring deformed by moving ahead of the plane containing the ring and in towards the jet axis, while the straight sections moved behind and away from the axis; all due to the effects of self-induced velocity (1), with higher self-induced velocity in the corner regions with high curvature, and zero self-induced velocity in the straight sections due to the lack of curvature. A more thorough description of the mechanism can be found in the above papers.

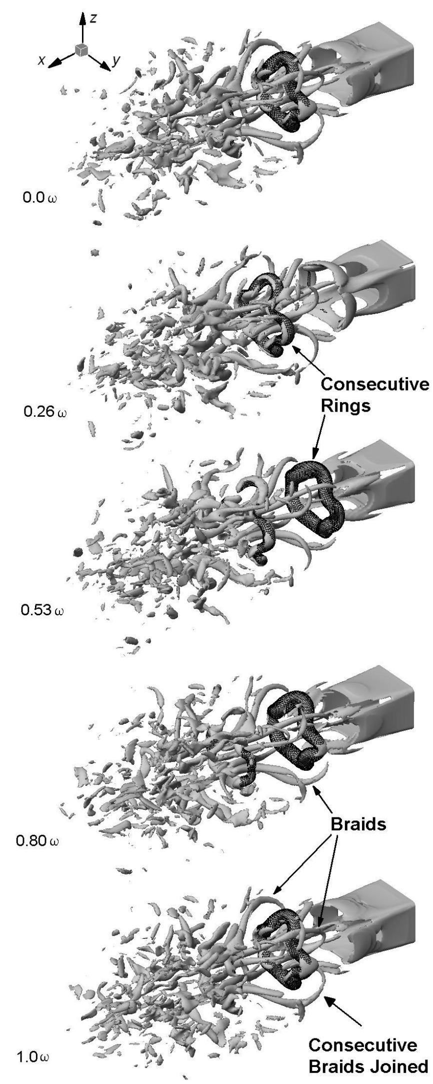

Figure 3: Dynamics of Coherent Structures in PRI as a function of dimensionless time, ω.

Long thin structures (braids) appeared between the rings, similar to braid vortices in a mixing layer [12]. Braids are created by instabilities in the mixing layer and are formed in counter rotating pairs. Since a vortex ring is essentially a mixing layer wrapped around onto itself the appearance of these secondary structures between vortex rings is expected and has been noted by the majority of authors investigating coherent structures in jets. In their studies of "side jet ejections" in circular jets, [13] added the contribution of stream-wise vortices to their proposed jet-spreading model of 1989 that only included ring vortices.

The braids were grouped in pairs similar to a mixing layer, one pair per corner, and counter-rotating such that fluid was drawn between them from within the jet core and expelled outwards. The downstream ends of one set of braids on the longer side of the jet periodically joined with braids forming behind the upstream ring on the short sides of the jet, indicated by an arrow in figure 3. No such behaviour could be found in the literature.

Shear layer development in jets occurs due to entrainment of fluid from the surroundings and redistribution of fluid from the jet core. The effect of the different modes of coherent structures on the mean velocity profile of each jet is shown in figure 4. Mean velocity profiles are shown for each jet in the *yz* plane at the same distance downstream of the nozzle normalised to D_{PRI}. A snapshot of the coherent structures in the jet is also shown.

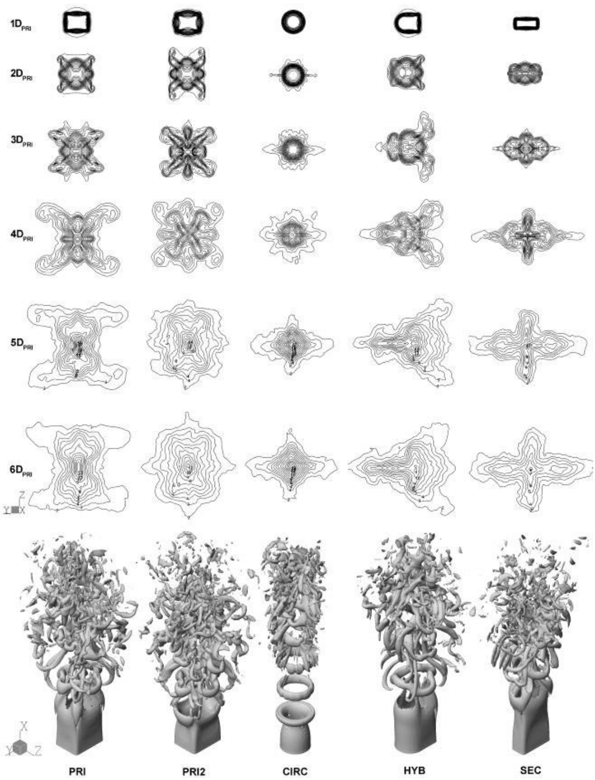

Figure 4: Development of Mean Velocity Profiles.

Although both primary jets produced the same general coherent structure behaviour, i.e. almost square rings and four pairs of counter-rotating braid vortices, the resulting shear layers were notably different. Due to the higher frequency in PRI2 the rings rolled up closer to the nozzle than those in PRI, initiating the shear layer spreading process somewhat sooner. The braid vortices contributed significantly to redistribution of momentum in the diagonal cross-stream directions of the shear layer. In PRI the rings switched axis once and then began to break up, so the fluid in them continued to convect in the same direction along the minor axis, with little spreading occurring in the major axis. The rings were preserved longer as a coherent structure in PRI2, allowing them to continue deforming and giving a more uniform shear layer by $6D_{PRI}$.

The dynamics of the jet SEC were similar to those of the rectangular jets of [5]. Because the corners were closer together the self-induced velocity of the corners was reinforced, compared with PRI where it was retarded by the straight sections. When viewed along the centreline axis, the rectangular ring switched axis by 90°, and remained like this until it dissipated into smaller structures. The stream wise vorticity only maintained one pair of braid vortices on either side of the jet, as opposed to the two pairs in PRI and PRI2. Braids associated with the shorter sides of the ring were consumed by larger structures almost as they were formed. Curiously, the braids actually became joined at the tails, rather than head-to-tail as in PRI and PRI2. Spreading of the shear layer occurred predominantly along the major and minor axes. On the major axis the contribution was dominated by the braid vortices, while on the minor axis it was by the ring vortices.

Instead of spreading uniformly in the radial direction, as one might intuitively expect, the jet CIRC actually exhibited some preferential spreading along the *y* and *z*-axes. This resulted in velocity profiles which were square, but rotated 45° to the axes. This was due to the peculiar braid structure that formed from the axi-symmetric rings. In PRI and PRI2, the high curvature corner regions provided locations of high stream-wise vorticity from which braid vortices could form. With a uniform initial stream-wise vorticity distribution in CIRC, braids were not triggered until instability waves deformed the ring such that stream-wise vorticity began to grow. This wave instability is well documented for isolated circular vortex rings and circular rings in jets; see for example [16] and [3]. For this simulation pairs of braid vortices of varying strength formed, two strong pairs aligned with the *y*-axis and four slightly weaker pairs aligned with the *z*-axis, resulting in more spreading on the axes. This is not a detailed investigation of the precise mechanisms of vortex deformation within circular jets, the important point is that the occurrence of the braids occurred much farther downstream in the circular jet than the rectangular ones, and they were much weaker than for the other jets, due to the initially uniform curvature of the rings.

By contrast, braid vortices of nearly equal strength formed in HYB at approximately the same time on the rectangular and circular sides. While there were two counter-rotating pairs on the square side, one for each corner as in jets PRI and PRI2, there was only one pair on the circular side, similar to SEC. The rectangular side deformed in much the same manner as in PRI and PRI2. Although the self-induced velocity of the circular side of the ring was uniform around the circumference due to its uniform curvature, the circular part of this coherent structure was effectively pinned or hinged at the points of joining to the rectangular side and as a result this part of the structure folded in towards the axis as it tried to accelerate ahead of the rest of the ring. This resulted in cross-axis mixing in HYB, the only jet to exhibit such behaviour. This can be seen clearly in the time series of figure 5 in which the circular side folds inwards, eventually crossing the axis at about x/D = 4. The movement of the ring across the central axis also forced the braids to cross the axis by about *x*/D = 3. These correspond to the locations in figure 1 where there was a reduction in entrainment on the round side. Figure 4 shows that HYB spread along the major axis on the circular side, which was due to the convection of the tail ends of the braid vortices in this direction, with no direct contribution from the ring structures. This reinforces the point that stream-wise vortical structures are at least as important as ring vortices in the near-field shear layer development of jets.

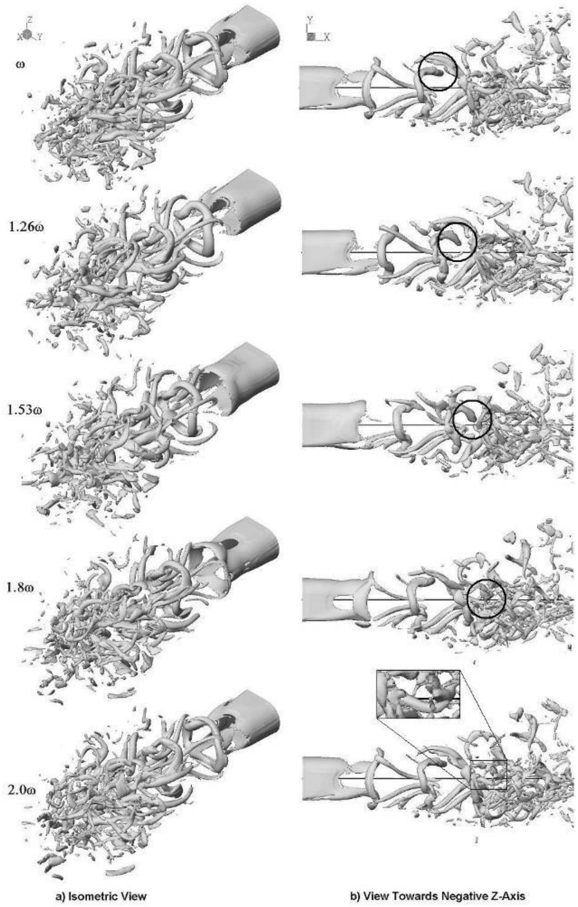

Figure 5: Coherent Structure Dynamics in HYB.

A hybrid jet was simulated with an aspect ratio of 2.2:1 [8], however, the curvature of the circular side was so close to the curvature of the rounded corners of SEC that there was no significant difference between SEC and this geometry. As a result the coherent structure dynamics were almost exactly the same, in terms of vortex ring deformation as well as in the generation and convection of stream wise coherent structures. This lead to virtually the same shear layer development as in SEC, with the shear layer spreading along the major and minor axes. For this reason the results were not shown here.

Conclusions

For the two aspect ratio nozzles, it was only the lower ratio one that showed any significant change in the shear layer development when one side of the nozzle was rounded. The influence of nozzle geometry can be seen in two areas, the shape of the ring and the number of stream wise structures that formed due to discontinuities in the curvature of the ring.

The size and relative proximity of discontinuities in the vortex ring determine how strongly a vortex ring deforms. There was little difference between PRI and the rectangular side of HYB because 90° bends produce strong deformation behaviour. The circular side of HYB behaved nothing like CIRC because even the small discontinuity where the circular side joined the straight sections dominated over the uniform curvature section and caused the ring to deform in the manner it did.

Spreading of HYB along its major axis on the circular side was due to the single pair of braids that formed on that side. There appears to be a correlation between those jets that spread along their axes and those jets with only a single pair of braid vortices per side.

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