Abstract
This study is part of larger program aimed at providing an improved understanding of reacting and non-reacting swirling flows and at establishing a comprehensive database which will become an international benchmark for validating and developing numerical tools. The focus of this paper is on non-reacting swirling flows of air in air obtained at a single jet velocity and for two different swirl numbers. Only one co-flowing air stream is swirled.

Laser Doppler Velocimetry is used to map the three components of velocity, turbulence levels and shear stresses ($<uv>$ and $<uw>$). For both swirl flows investigated, recirculation zones are established above the burner’s exit plane. It is shown that the onset of vortex breakdown and hence a second recirculation zone depends not only on the swirl number but also on the other flow parameters. The axial momentum of the central jet and the primary axial swirling channel, or the Reynolds numbers of these, appear to be critical parameters. The spreading rate of the flowfield is believed to be largely controlled by these parameters.

This paper illustrates the importance of these issues by showing measured flowfields for two non-reacting jets with different swirl number and different axial momentum in the primary air stream but the same momentum in the central jet.

Introduction
The positive effects of swirl are associated with flow recirculation. Recirculation zones play an important role in flame stabilization since they constitute a well-mixed zone of hot combustion products and act like storage of heat and chemically active species [8]. Recirculation also creates regions of zero axial velocity near which the flame speed and flow speed are properly matched [9]. The presence of a second central recirculation zone in swirl-stabilised flames has been previously reported and attributed to the high tangential velocities (swirl numbers) involved with such flows [6]. The attainment of axial recirculation and vortex breakdown has been linked to a critical swirl number, $S$, and its presence at $S < 0.6$ is not anticipated [5].

The aims of the present research are to clarify that, for non-reacting unconfined swirling flows, a sufficiently large swirl number, alone, may not necessarily favour the onset of vortex breakdown in comparison with a flow configuration involving a smaller swirl number. The characteristics of vortex breakdown adopted in the paper are the formation of a stagnation point on the axis and a sudden widening of the vortex core because of a region of reversed axial flow [7]. Results will emphasize the view that the swirl number, as an integral parameter, is insufficient in describing the character of swirling flows and that additional nondimensional parameter(s) need to be adopted to fully characterise the near-field behaviour ($x/D\text{_{swirl}}<5$) of turbulent flows with swirl distribution [4].

Experimental
Swirl is induced aerodynamically into the primary (axial) air stream at a distance of 300mm upstream of the burner exit via three tangential swirl ports. The geometric swirl number, $S_{g}$, is used for the quantitative representation of swirl intensity, and is expressed here by the ratio of integral (bulk) tangential to primary axial air velocities ($W_{s}/U_{s}$) above the annulus. By changing the relative magnitudes of the tangential and axial air flowrates, the swirl number can be varied.

The burner design employed is believed to offer relative simplicity and has well defined and uniform boundary conditions [1]. It has a 50mm diameter ceramic faced bluff-body with a 3.6 mm central fuel jet (Fig 1). Surrounding the bluff-body is a 60mm diameter annulus with a 0.2mm thick lip. The burner is housed in a secondary axial (co-flow) air tunnel with a square cross-section and 130mm sides. Outside this layer, the secondary axial air velocity had a mean value of $U_{e}$ 20 m/s and an average free stream turbulence level of about 2%.

Figure 1 Burner configuration and relevant velocities

For the Laser Doppler Velocimetry measurements a two-component Aerometrics system was used in the forward scattering mode. This configuration increased the spatial resolution by allowing laser scattering from the probe volume to pass through a 100µm spatial filter in the receiver module before being picked up by the PMT’s. This length scale is taken here as the spatial resolution. A Spectra-Physics Stabilite-2017 Ion laser pumped this LDV system and the average power at the probe
volume was 200mW. Seeding, in the form of deagglomilated 0.3µm alumina was applied to the primary (annulus) and secondary (co-flow) air streams and to the central fuel jet. An annular seeder, upstream of the burner face by 230mm, surrounds the burner and is necessary to extend the LDV measurements out beyond the burner and into the co-flowing air. Hot wire measurements in the secondary air found that the boundary layer resulting from such a configuration to be of the order of 5mm thick [1]. At each axial position scanned, joint measurements of the U-W components along a series of radial locations were initially taken and then another scan, at 90° to this, was done at the same radial points for the U-V. Table 1 shows the flow conditions for these tests.

<table>
<thead>
<tr>
<th>Flow condition</th>
<th>U_j,m/s</th>
<th>W_s,m/s</th>
<th>U_j,m/s</th>
<th>S_g</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR - SMA2</td>
<td>16.3</td>
<td>25.9</td>
<td>66</td>
<td>1.6</td>
</tr>
<tr>
<td>NR - SMH2</td>
<td>29.7</td>
<td>16.0</td>
<td>66</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 1 Experimental Conditions

Results & Discussion

Flow Condition NR-SMA2 (Figures 2, 3): Contour plots of the time averaged U velocity reveal that a relatively large stagnation/recirculation zone develops above the ceramic bluff body. Its dimensions extend axially to ~70mm and radially from just inside the annulus, at about (r ~22mm), to about 5mm from the burner centreline. The jet, whilst just still being capable of penetrating this stagnating body of air, continues to decelerate as it passes the apex of this body at around 90mm before the U velocity starts to pick up once again. However, the exceedingly low centreline velocities at 90mm may indicate that the flowfield was on the verge of establishing a central recirculation zone there, and that vortex breakdown was imminent [4]. The W velocity contour plot also shows that the rotating nature of the whole flowfield and that, as a consequence of the swirl, the W component is also present in the co flowing secondary air stream to radial distances of 40mm. This leads to the formation of a sparse flow regime, where, through a centrifugal like influence, the high swirl number being used is believed to be responsible in spreading the flowfield outwards. Greater degrees of swirl have also previously been found to lead to increased radial spread of swirling jets [3]. Measurements also reveal a small, widening, counter-rotating body of air that exists just outside the burner (r>30mm) in the co-flowing air and does not reach any appreciable height or strength. Above the ceramic face of the burner and very close to the jet, at a radial distance of 3-8mm, there also exists a strongly rotating zone of air where W_max is around 12m/s and the rms fluctuation of rotational velocity, W, is seen to increase.

Flow Condition NR-SMH2 (Figures 4, 5): Although the contour plots of the U velocity also show that a stagnation/recirculation zone develops above the ceramic bluff body, it has now shrunk in size and diminishes at a downstream distance of 25mm. Now the primary axial momentum is much higher than that for NR-SMA2 by a factor of three (ρAu^2 ⋅ u_1 / ρAu^2 ⋅ u_2 ; where 1 and 2 refer to NR-SMH2 and NR-SMA2 respectively and ρAu is the mass) and at an axial distance of about 50mm, a central recirculation zone and vortex breakdown has been achieved with a downstream stagnation point at around 110mm. The jet fails to penetrate this recirculating body of air and it thus forms an aerodynamic blockage above the burner. Flow condition NR-SMH2 also differs from NR-SMA2 in the extent to which the flowfield extends in the horizontal direction. The W velocity contour plot now shows that the flowfield is less able to convect the W component outwards into the co-flowing secondary air stream. The zero contour line of this velocity remains essentially above the burner annulus (r ~30mm) with a slight inclination inwards up to 60mm downstream from the burner. The counter-rotating zone of air outside the burner is also present with flow condition NR-SMH2 and now larger compared to that of NR-SMA2. These weak negative swirl velocities may arise due to some inherent noise levels in the data taken or the development of some weak edge vortices at the exit plane of the wind tunnel. Further tests are needed to corroborate either of these probabilities. The maximum value for the W velocity now occurs not directly above the annulus, as was the case with NR-SMA2, but at an axial distance of 40mm above the face of the burner (r ~15mm). This may be due to the width of the flowfield downstream of the burner annulus since NR-SMH2 has a more compact (narrower) flow regime. Radial conservation of momentum means that higher velocities must be expected across the width of the flowfield.

Vortex breakdown and flow recirculation that occurs in jet NR-SMH2 leads to an aerodynamic blockage on the centreline and faster decay in jet velocity and turbulent kinetic energy, k = (u'^2 + v'^2 + w'^2)/2 which is clearly shown in Figure 6. This graph also reveals that NR-SMA2 indeed comes very close to having a stagnation point on the centreline at ~90mm. The central blockage also leads to axial velocities off the centreline, say at r = 15, 20 and 25mm being higher in NR-SMH2 than in NR-SMA2. This behaviour is expected and occurs since the fluid is forced to accelerate through the restricted cross-sectional area between the surrounding stagnant fluid and the edge of the recirculating vortex [3].

It appears controversial that vortex breakdown is achieved in the flow with the lower rather than the higher swirl number. However it is evident from the results presented here, as well as a further set of results which will be presented elsewhere [2], that the axial momentum (Reynolds numbers) of the swirling annulus and the central jet also play a major role in determining the onset of vortex breakdown.

Conclusions

The combination of lower swirl number and higher primary axial velocity (Uj) has been found to lead to a more compact flow field and to the establishment of a strong rotating axial recirculation zone. This took on the form of a stagnating body of air or aerodynamic blockage that was downstream of the burner face by about one bluff body diameter (~50mm). The presence of this blockage does not lead to higher levels of turbulence kinetic energies on the centreline. The differences in the nature of the flow fields involved, at the two swirl numbers covered, have also been described with some detail. The present results have also shown that, in comparison to a non-reacting swirl flow with a smaller Sg, a sufficiently high value of swirl number, alone, may not necessarily favour the establishment of vortex breakdown and hence the downstream axial recirculation zone.

Whilst these results are only preliminary for us, they are intended to signify the importance of choosing the appropriate combination of swirl flow parameters (Uj and Wj). It is also believed that more work should be done to characterise the influence of these parameters in addition to others, such as Uj, on the shape of the flowfield and retaining vortex breakdown.

Acknowledgement

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References


Figure 4 NR-SMH2 contour plots (top: U vel, bottom: W vel)

Figure 5 NR-SMH2 U-V vector plot

Figure 6 Centreline U vel and turbulent kinetic energy decay