ABSTRACT

A propane-fueled research combustor has been designed and developed to investigate lean blowouts in a simulated primary zone of the combustors for aircraft gas turbine engines. To better understand the flow development and to ensure that the special provisions in the combustor for optical access did not introduce undue influence, measurements of the velocity fields inside the combustor were made using laser Döppler anemometry. These measurements were made in isothermal, constant density flow to relate the combustor flow field development to known jet behavior and to backward-facing step experimental data in the literature. The major features of the flow field appear to be consistent with the expected behavior, and there is no evidence that the provision of optical access adversely affected the flows measured.

NOMENCLATURE

- $a$: Upstream distance from step, defining effective origin of merged jets
- $D_L$: Combustor diameter
- $h$: Step height
- $i$, $j$: Cartesian tensor co-ordinate directions
- $l_m$: Mixing length
- $L/D$: Length to diameter ratio
- $M_{O/I}$: Momentum ratio of outer jet to inner jet
- $n$: Exponent in definition of boundary layer velocity profile
- $R$: Radius
- $R_f$: Fuel tube interior radius
- $R_{1/2}$: Radius at which $\bar{u}$ has fallen to $1/2 \bar{u}_c$
- $R_{u = 0}$: Radius at which $\bar{u} = 0$
- $U$, $U_{AVE}$: Mass-averaged axial velocity
- $U_L$: Mass-averaged axial velocity in combustor
- $U_1$: Initial mass-averaged axial velocity of center jet
- $\bar{u}$: Time-mean axial velocity
- $u_{\text{max}}$: Maximum axial velocity in X, Y scan
- $u_c$: Time-mean axial velocity on combustor centerline
- $u_{c,\text{min}}$: Time-mean minimum centerline axial velocity
- $u_1$, $u_2$: Maximum and minimum velocity in shear layer
- $u_f$: Fuel jet axial velocity
- $u'$: Fluctuating axial velocity
- $\bar{u}_i$, $\bar{u}_j$: Reynolds stresses
- $\bar{v}$: Time-averaged radial velocity
- $v'$: Fluctuating radial velocity
- $X$, $Y$: Diametral co-ordinate directions
- $y$: Distance normal to wall
- $Z$: Downstream co-ordinate direction from combustor step plane
- $z_p$: Conditional potential core length
- $\delta$: Shear layer width
- $\eta$: Dimensionless distance across shear layer
- $\xi_2$: Dimensionless radius

INTRODUCTION

A propane-fueled research combustor (Fig. 1) has been designed (Sturgess et al., 1990) and developed (Sturgess et al., 1990; Heneghan et al., 1990) to investigate lean blowouts in a simulated primary zone of combustors for aircraft gas turbine engines. The fundamental flow and heat release features of a gas turbine combustor primary zone, within which the flame is held, are generated by the geometrically simple design of the research combustor.
The construction of the window section results in a duct cross-section as shown in Fig. 1. The quartz windows are on a square of 152 mm inside diameter, within which the Inconel corner inserts form a circle of 84 mm. This results in a window width of 71 mm, and the length of the windows is 457 mm. The cross-section of the window section is duplicated in the extension chimney, fabricated of Inconel.

The hybrid cross-section of the combustor described above represents a hard-won compromise between the demands for geometrical simplicity and flow two-dimensionality, and the need for straightforward optical access to allow use of laser diagnostics. The flat windows avoid laser beam distortion, while the corner fillets distribute vorticity generation and reduce secondary flow developments due to interaction of the wall boundary layers on the flat windows. If unaddressed, corner-derived secondary flow vortices could influence combustion stability by providing spurious flame holding.

While the cross-section of the combustor was designed to ameliorate the magnitude of secondary flow developments, it is not possible to entirely eliminate the local concentrations of vorticity where the circular–arc corner fillets run into the flat windows. However, the vorticity should be reduced in strength and distributed to a degree that secondary flow development does not substantially influence the bulk flow development in the combustor. While computational fluid dynamics (CFD) analyses showed that the introduction of the corner fillets resulted in the anticipated favorable modification of flow behavior, it was still necessary to demonstrate experimentally that such is the case. To this end, velocity field measurements were made in the combustor under isothermal, constant density conditions. These measurements also serve to contribute to the understanding of the flow development in the combustor; in addition, they provide initial condition information and baseline data for testing subsequent CFD analyses employing blowout models being developed as part of this research.

LDA ARRANGEMENT

A custom–designed laser–Doppler anemometer (LDA) system was used for all of the velocity measurements. The LDA uses the green (514.5 nm) and blue (488 nm) lines of a 15 W Argon–ion laser as a source; two measurement channels of this system were separated by polarization, while the third uses the blue beam. The third channel optics were set up normal to the two–channel optics, and the scattered signal was collected in a forward direction at 10 degrees off–axis. The effective probe volume was 50 x 300 x 750 μm. The instrument incorporates Bragg cells with a 5 MHz frequency shift for unambiguous measurements in recirculatory flows. A unique three–channel co–incidence circuit with a 10 μs window for rapid validation of acquired data was also incorporated. This assists the integration of the LDA with CARS, Raman or Rayleigh spectroscopic techniques to be used later with reacting flows.

A proprietary fluidized–bed seeder was used to inject submicron–sized Al2O3 or SiO2 seed particles into the flowing streams. The primary source of error in the measurements is the statistical bias of the final measured velocity towards higher mass fluxes when number–weighted averages are used to calculate stationary statistics. Chen and Lightman (1985) and Glass and Bilger (1978) have discussed bias correction schemes. Seeding of the fuel and air stream separately and
For reasons of safety and economy, the fuel stream was made air rather than gaseous propane. On a Reynolds number basis, the conditions at which the majority of the results to be presented were obtained correspond in this simulation to an actual lean blowout point for which the fuel jet is turbulent at inlet (Reynolds number > 9,000) with an air jet Reynolds number appropriate to an equivalence ratio of about 0.5. The mass average axial velocities for the fuel jet, air jet and combustor at this condition are respectively, 1.98, 20.6 and 3.06 m/s.

RESULTS

Inlet Conditions

Scattered signals were detected by TSI Counter Processors, and were processed by custom-designed software to yield intensity, shear stresses, skewness and kurtosis, and pdf's. Typical sampling rates were up to 1 kHz. At each spatial location in the combustor, a total of 4096 realizations were acquired. A portion of these data (up to 2 percent), whose departure from the mean exceeded three standard deviations, was filtered to eliminate spurious signals due to seed agglomeration. Finally, a subroutine was used to correct for any particle and density biasing effect, (non-reacting and reacting flows).

Error Analysis

Both the fuel stream and air stream flows were monitored and controlled by separate electronic flow control units to within 2 percent. Also, mass conservation balances in the exit plane of the fuel tube provided an additional cross-check against flow meter readings. After allowing for seeding bias, for single-stream seeding with the relatively high sampling rates used, the uncertainty in the measurement of mean velocity was 1 percent, for rms velocity 5 percent, and for skewness and flatness, 7 percent. The long-term repeatability was found to be within 5 percent for the turbulence quantities.

Traverse Axes

The combustor is mounted vertically in the facility (Sturgess et al., 1990) and its centerline constitutes the z-axis. Zero z is taken as the plane of the step. The x and y-axes are diametral to the combustor cross-section, with the x-axis aligned with the LDA axis. The axis convention is shown in Fig. 1. Velocities parallel to and increasing in the direction of the z-axis, and velocities normal to and directed away from this axis, are also considered positive.

Windows

The geometric window sizes in the combustor, the LDA traverse mechanism, (Sturgess et al., 1990) and the LDA beam focussing together define the effective windows within which data may be taken. This access window is given by -68.7 <= x <= +68.7 mm, and -22 <= y <= +33 mm; in the downstream direction it is +2 <= z <= +358 mm.

TEST CONDITIONS

Separate diametral traverses of the fuel jet and annular air jet were made by the LDA at the step with the combustor body removed, for a variety of inlet mass flow rates covering fuel jet Reynolds numbers from 1,733 to 17,333, and air jet Reynolds numbers from 7,233 to 72,322. Air was used for the fuel jet was based on the experimental data of Rehme (1974), corrected to the radius ratio of 0.675 appropriate for the research combustor, and Nikuradse-profiles with n appropriate to 60,000 Reynolds number. This procedure resulted in a radius...
at which the profile exhibited its maximum of 16.537 mm, or 46.7 percent of the annular height from the jet inner radius.

The radial profile \((y\text{-scan})\) of measured time-mean axial velocities, in the form of \(u/u_{\text{max}}\), for a Reynolds number of 83,330 was much flatter than for fully-developed flow, and the peak velocity occurred at about 15 mm radius, i.e., inwards-peaked compared to anticipation. There was considerable asymmetry across the traverse, with the ratio of maximum time-mean axial velocity to mass-averaged axial velocity, \(u/u_{\text{ave}}\), being 1.214 for negative \(R\) and 1.186 for positive \(R\). For an \(x\)-scan radial profile, the position of the maximum velocity was at a radius \(\pm 14.6\) mm, i.e., slightly more inwards-peaked than the \(y\)-scan profile, while the values of \(u_{\text{max}}/u_{\text{ave}}\) were about 1.23, i.e., slightly more peaked.

The radial profile of local axial turbulence intensity \(u'/u\), from a \(y\)-scan at 83,330 Reynolds number was fairly flat at about 6 percent across the center-section of the annular jet. Increases at the edges of the jet were due not only to the mean axial velocities decreasing, but also to an increase in the local fluctuating velocities due to the increased shear generated at the tube walls.

Despite the careful design of the inlet, it is apparent that the annular air jet is not being fed uniformly around its circumference, and that a radial velocity component is being developed which results in an inwards flow towards the outer wall of the fuel tube.

With the combustor body mounted on the step, the closest axial station to the step at which LDA data can be taken is 5 mm. At this position with the combustor mounted and both jets flowing, the annular air jet takes control of the fuel jet. This can be seen in Fig. 2 for \(x\)- and \(y\)-scan diametral traverses, where the time-mean axial velocity divided by the mass-averaged axial velocity in the combustor, \(u/U_{\text{L}}\), is shown. This traverse is for a fuel jet Reynolds number of 11,320 and an air jet Reynolds number of 56,413. Comparison of the \(x\)- and \(y\)-scan data in the central region of the traverses reveals that fuel jet profiles have been distorted by the influence of the non-uniform air jet to produce a flow reduction in the +X, +Y quadrant, and a small reverse flow region in the \(x\)-scan. Thus, the relatively minor non-uniformities in the isolated fuel and air jet flows have been magnified when both jets are flowing to result in significant distortion of the lower momentum fuel jet.

Fig. 3 is a repeat of the \(y\)-scan of Fig. 2 at an increased density of measurement; the \(v/U_{\text{L}}\) profile is also included. The improved resolution of the annular air jet can be seen. These profiles would represent adequate initial condition information for computational fluid dynamics calculations. The appropriate turbulence information is shown in Fig. 4.

**General Flow Development**

Selected diametral (\(x\)-scan) profiles of non-dimensional time-average and fluctuating velocities at various axial positions in the combustor, Figs. 5 through 10 inclusive, together with Figs. 3 and 4, present the general flow development in the combustor at the selected operating conditions.

The distinct high velocity co-annular jet and the low velocity central jet (Figs. 3 and 4) quickly merge as the annular jet fills in the velocity defect represented by the central jet,
Fig. 4  High Resolution Y-Scan of Fluctuating Velocity Profiles at $z = 5$ mm; Combustor Inlet Condition

Fig. 5  X-Scan Diametral Profiles of Mean Velocities at $z = 55$ mm

Fig. 6  X-Scan Diametral Profiles of Fluctuating Velocities at $z = 55$ mm

Fig. 7  X-Scan Diametral Profiles of Mean Velocities at $z = 138$ mm
Fig. 8 X-Scan Diametral Profiles of Fluctuating Velocities at z = 138 mm

Fig. 9 X-Scan Diametral Profiles of Mean Velocities at z = 220 mm

Fig. 10 X-Scan Diametral Profiles of Fluctuating Velocities at z = 220 mm

Fig. 11 represents non-dimensional time-average axial and radial velocity profiles from a y-scan at an axial station of 138 mm. These plots should be compared with those in Fig. 7 (x-scan) to obtain an assessment of the downstream asymmetry introduced into the flow by the upstream distortions due to the individual jet irregularities, Fig. 2.

Fig. 11 Diametral Profiles of Mean Velocities from a Y-Scan at z = 138 mm; for an Assessment of Flow Distortion
The general characteristics are completed by Fig. 12 that gives centerline traverses of non-dimensional time-averaged axial velocity. This shows that the initial momentum difference between the jets is so large that entrainment of the central jet by the annular jet results in the formation of a central recirculation bubble. Centerline axial velocity recovers and then overshoots as the annular jet expands to fill the central velocity deficit. Finally, the centerline axial velocity decays. High fluctuating axial velocities are associated with the fore and aft stagnation points of the central recirculation bubble.

**Fig. 12** Variation of Axial Mean Velocity Along Combustor Centerline, Showing Central Recirculation Zone

** Anaheim of Results**

**Near-Field**

The salient features of the near-field velocity development in the research combustor are displayed in Fig. 13, which is constructed from radial profile information.

Shown in Fig. 13 are data-points and lines that represent the contours where the time-mean axial velocities are zero. These define the existence of the two recirculation zones noted above; one is associated with the step as expected, and the other on the centerline of the combustor is generated by jet interaction. These zero mean axial velocity lines delineate the beginnings and ends of the two separated flow regions, but not their radial extents. The central recirculation bubble is positioned on the combustor centerline at 14 mm downstream from the step, and extends downstream for another 18 mm.

Shear layers originate at the confluence of the central fuel jet and the concentric air jet. Shown are lines representing the locus of points where the local mean axial velocity is equal to the fuel mean axial velocity at the step, and also where it is equal to the maximum in the jet shear layer. The position of the inner edge of the jet shear layer can be checked by also plotting the locus of the radii where the fluctuating axial and radial velocity components exhibit a distinct increase from the fuel jet inlet values. This definition of the shear layer inner edge is at consistently reduced radii compared to the former definition.

**Fig. 13** Salient Features of Near-Field Development

The downstream distance where the inner edge of the jet shear layer intersects the combustor axis defines a conditional potential core length for the fuel jet. The fact that the fluctuating velocity definition of the shear layer inner edge is at smaller radii than the time-mean axial velocity definition is due to the existence of initial turbulence associated with boundary layer buildup on the interior surface of the fuel tube, upstream. Normal shear layer growth is linear, rather than the concave-downwards curve seen in Fig. 13. This curvature is induced by the presence of the central recirculation bubble.

The dimensionless potential core length, $z_p/R_f$, is equal to 2.4. This value is in very good agreement with the theoretical calculations of Abramovich (1963) for co-flowing jets with boundary layers.

The momentum difference that exists between the two jets initially results in entrainment of the low momentum fuel jet by the high momentum annular air jet surrounding it. The momentum difference is large enough to cause the centerline recirculation zone to form in the fuel jet. The strength of this effect can be characterized by the depression of the initial mean axial velocity on the combustor centerline, ($u_{c,0} - u_{c,ax}$). This velocity difference can be non-dimensionalized by the maximum overall change, on a mass-average basis, that the center jet can undergo, i.e., $(U_f - U_L)$. Entrainment
considerations would relate this ratio to the square root of the jet momentum ratio $M_0/M_1$.

Fig. 14 is a plot of this relationship for the research combustor at a variety of operating conditions with air/air, air/nitrogen and air/propane (reacting) flows, and for some similar geometries from the literature, i.e., Habib and Whitelaw (1979), Johnson and Bennett (1981), and Owen (1975). All of the present data points represent actual reverse flow conditions; while Habib and Whitelaw (1979) and Johnson and Bennett (1981) have points in which depression of the initial centerline velocity takes place, but no actual reverse flow occurs. This figure shows good agreement between the present data and those of other researchers.

Fig. 14  Dependency of Strength of Centerline Recirculation on Jet Momentum Ratio, and Comparison with Data from the Literature

When considering Fig. 13, it was found that the locus of the radial positions in the jet shear layer where the fluctuating velocity components $u'$ and $v'$ reached a minimum coincided with the locus of the maximum mean axial velocity, and the maximum values of these components coincided with the loci of maximum velocity gradients in the mean velocity radial profiles. This is the case to a value of $z$ equal to 35 mm, but only reasonably so at a station of $z$ equal to 55 mm. For example, compare Figs. 5 and 6.

The implication of this behavior is that the local turbulence is generated by the local shear, through the local mean velocity profiles. This being so, the Reynolds stresses in the jet shear layer could be described by Prandtl's (1925) mixing length model (Abramovich, 1963),

$$ u'_i u'_j = \frac{2}{m} \left( \frac{du_i}{dx} \right) \left( \frac{du_j}{dx} \right) $$

where for round jets the mixing length $l_m$ is given by,

$$ l_m/\delta = 0.079 $$

and $\delta$ is the shear layer width.

Fig. 15 compares a Reynolds stress radial profile calculated from Eqs. (2) and (3), and non-dimensionalized by the square of measured local mean axial velocity, with the measured profile at $z$ equal to 25 mm. The velocity gradients used in Eq. (2) were obtained from the measured mean velocity profiles.

Fig. 15  Comparison of Measured and Calculated Reynolds Stresses in Jet Shear Layers at $z=25$ mm

By a $z$ of 55 mm, the agreement between measured and calculated Reynolds stress profiles is only fair. This must be due to the upstream presence of the centerline recirculation zone, and the fuel jet high initial turbulence due to the presence of the acoustic isolator. By this axial station, the transport of turbulence is apparently becoming important in comparison with local shear generation.

The behavior of the shear layers with respect to Reynolds stresses suggests that the time-mean axial velocity profiles at different axial positions in these layers might be self-similar, that is, of the same shape but differing by a scale factor. To test this, several velocity profiles in both inner and outer layers were plotted in the dimensionless form,

$$ \frac{u_1 - u}{u_1 - u_2} = F \left( \frac{y - y_2}{\delta} \right) $$

where $u$ is the time-mean axial velocity in the shear layer at position $y$; $u_1$ and $u_2$ respectively are the maximum and minimum velocities bounding the shear layer and $\delta$ is its width. Inner and outer shear layer data were obtained from radial profiles at positive and negative radii for $x$-scans and $y$-scans at downstream positions of 25, 35 and 55 mm; the inner shear layer width at any axial position was defined from the positions of maximum jet velocity to that of the fuel jet (see Fig. 13), and the outer shear layer width at any axial position was defined from the positions of maximum jet velocity to the zero velocity line in the step recirculation zone. The shear layer profiles are shown in Fig. 16.
Fig. 16 Self-Similarity of Mean Axial Velocity Profiles in Jet Shear Layers, and Comparison with Schlichting's Profile

Fig. 16 demonstrates that the axial velocity profiles at the three positions downstream collapse onto a common relationship. There is no difference between the inner and outer layers. The flow asymmetries present in the flow should be recalled. The profiles, therefore, may be considered as being similar. Shown also on the figure is Schlichting's classical plane shear layer velocity profile (Schlichting, 1960),

\[
\frac{u_1 - u}{u_1 - u_2} = (1 - \eta^{3/2})^2
\]

(5)

where,

\[
\eta = \frac{(y - y_2)}{\delta}
\]

(6)

The correlated data have the same general form as Eq. (5), but differ from it in fullness. This difference is undoubtedly associated with the streamwise curvature of the jet shear layers in the research combustor.

Far-Field

In this region the individual jets interact vigorously with each other and have merged by 138 mm from their confluence (Figs. 7 and 8). Having lost their individuality, subsequent development takes place as though the two jets were a single round jet.

One of the major characteristics of the round jet is the development of self-similar profiles. The condition of similarity in the radial profiles of time-mean axial velocity is examined in Fig. 17 for axial stations of 138, 220, 275, 300, 330 and 358 mm by plotting the dimensionless radial profile of mean axial velocity \(u/u_c \) against \( R/R_{1/2} \) where \( R \) is radius and \( R_{1/2} \) is the radius where the velocity \( u \) has fallen to one half of its centerline value \( u_c \). The data for \( \pm R \) and \( x- \) and \( y- \)scans, are included.

Fig. 17 Self-Similarity of Mean Axial Velocity Profiles in Far-Field, and Comparison with Shapiro's Submerged Round Jet Profile

Fig. 17 contains a line (with correlation coefficient 0.9998) representing Forstall and Shapiro's (Abramovich, 1963) data for submerged round jets with a variety of blowing ratios. A curve fit to the present data agrees excellently with the curve for Forstall and Shapiro's data out to a dimensionless radius of about 1.5, after which the two curves approach their own boundary conditions (i.e., submerging jet or step-recirculation).

The effective origin (point source) of the apparent single jet can be found by extrapolating the locus of the radii \( R_{1/2} \) for various axial stations backwards until it intercepts the combustor axis. This yields an effective origin that is about 140 mm upstream of the step.

With the effective origin of the combined jet so-determined, the turbulence profiles in the far-field region can be compared with the self-similar form of the turbulence profiles from Wyganski and Fiedler's round, free jet (Hinze, 1975). The similarity-form used is the dimensionless radius \( \xi_2 \), where

\[
\xi_2 = \frac{R}{(z + a)}
\]

(7)

and \( a \) is the distance upstream from the physical origin of the individual jets to the effective origin of the merged jets.

Fig. 18 compares the dimensionless fluctuating velocity \( u'/u_c \) against \( \xi_2 \) for \( z's \) of 275, 330 and 358 mm for \( \pm R \) from an \( x- \)scan. The line represents Wyganski and Fiedler's self-similar data to a correlation coefficient greater than 0.999. It can be seen that the turbulence profiles do not collapse onto a similar curve, but increase in intensity with increasing axial position. The behavior for the \( v'/u_c \) profiles is the same.
equivalent radius and h is the step height. The line representing the data is a 5th-order polynomial with a correlation coefficient of 0.9987. A portion of this curve appears in Fig. 13.

Fig. 18 Self-Similarity of Fluctuating Velocity Profiles in Far-Field, and Comparison with Wyganski and Fiedler's Free Round Jet Profile

The behavior of the present turbulence profiles is in sharp contrast to those of Wyganski and Fiedler's round jet, and are in direct conflict with Fig. 17 where the time-mean axial velocity profiles are shown to be self-similar. The inevitable conclusion from this conflict is that the fluctuating velocity profiles in the far-field are not directly associated with or derived from, the mean velocity profiles at the same axial station. Thus, for the turbulence field, flow history effects, i.e., convection of turbulence, dominates.

If the turbulence profiles are plotted in the form of a local turbulence intensity \( u'/u \) and \( v'/u \) against \( \xi_2 \), and compared with Corrsin's isothermal, free, round jet (Hinze, 1975) a similar finding is obtained. The present \( u'/u \) on the jet centerline is about twice that of Corrsin's jet, while \( v'/u \) is in better agreement; in both cases the present turbulence intensities increase much more rapidly with increasing dimensionless radius due to the presence of the combustor wall condition.

Fig. 19 Comparison of Local Turbulence Intensities for Habib and Whitelaw with Research Combustor

Despite the turbulence intensities being about twice the free round jet values, they are in accord with what is to be expected for the research combustor geometry. Radial profiles of local turbulence intensity \( u'/u \) at several axial stations are compared in Fig. 19 with those measured in a similar geometry by Habib and Whitelaw (1979). The increases in intensity at larger dimensionless radii represent falling values of \( u \) as the inner edges of the step recirculation zone are approached.

Step Recirculation

The downstream extent of the step recirculation zone may be found by tracing the locus of zero axial mean velocity \( (R(u = 0)) \) from the individual radial profile measurements, such as Figs. 5, 7 and 9. This has been done for the \( x \)-scan profiles \( \pm R \) which cover a greater radial extent than the \( y \)-scan profiles; see Fig. 1. The results are plotted in Fig. 20 in the form of \( R(u = 0)/R_L \) versus \( z/h \), where \( R_L \) is the combustor equivalent radius and h is the step height. The line representing the data is a 5th-order polynomial with a correlation coefficient of 0.9987. A portion of this curve appears in Fig. 13.

Fig. 20 Definition of Step Recirculation Zone Length

Although there are some small differences, the data show that the step recirculation zone development is fairly symmetrical about the combustor centerline. The boundary marking the division between upstream and downstream flow exhibits at least one point of inflection. Along this line, the zero velocity point defines the center of the vortex, and this is shown on the figure at about 3 step heights downstream from the step. The approximate length of the recirculation zone is
found by extrapolating the fitted curve to a dimensionless radius of unity. Such extrapolation results in a value of about 7.7 step heights, i.e., a $z/D_t$ of about 3. When this value is compared with the collected step recirculation zone length experience (Morrison et al., 1987) for the test Reynolds number, the agreement is good.

**DISCUSSION**

Optical access to the research combustor is acceptable and permits the behavior of the flow field to be mapped with reasonable coverage of the important features.

Efforts to condition the inlet flows result in individual jet flows that are reasonably uniform. The provision of a necessary acoustic isolator (Heneghan et al., 1990) in the fuel jet supply tube elevates the central jet fluctuating velocities over what would normally be associated with straight pipe flow and also affect the mean profiles. When the jets co-flow and are enclosed, they interact extremely strongly, and the individual jet anomalies are amplified so that the symmetry downstream in the combustor is not especially good. This jet interaction effect is felt in the fuel jet upstream of the step, i.e., before the geometric enclousure of the two jets, and it changes the inlet profiles of the central jet from the free–flow ones.

The step generates a large wall recirculation that extends a considerable distance down the combustor. It appears to be fairly symmetric. Jet momentum effects result in the creation of a small, central recirculation just downstream of the fuel jet discharge.

Outside the confines of the step recirculation and downstream of the central recirculation, the jet development takes place apparently largely unaffected by the presence of the recirculation zones. This time–mean development, in both near–field and far–field regions, is self–consistent, and is in good agreement with classical jet and shear layer behavior described through measurements in the literature. The initial turbulence generation in the jet shear layers is in accord with Prandtl’s mixing length theory, but downstream of the central recirculation bubble and after the end of the fuel jet conditional potential core the high initial level of turbulence and the transport of turbulence, i.e., flow history effects, start to dominate. Downstream, the individual jets merge into a single, central jet that has many of the time–mean characteristics of the free jet and the submerged round jet. In this region the turbulence profiles are totally unassociated with the local velocity profiles.

There is no evidence that the special, non–axisymmetric cross-section of the research combustor influences the isothermal flow development to any serious degree. The influence of mass transfer, chemical reaction, and heat release on this flow field development will make an interesting future study.

**CONCLUSIONS**

1. The optical access in the research combustor is adequate to establish the major flow features.
2. Reliable LDA measurements of time–mean and fluctuating axial and radial velocity components have been made for the isothermal flow condition.
3. Three regions of flow development were observed: a near–field region, a far–field region, and a step recirculation region. In the near–field shear layer development leads to a potential core, within which is a recirculation bubble generated by the jet momentum ratio. In the far–field the individual jets have lost their identity and exhibit self–similarity. The step recirculation bounds the near–field and part of the far–field regions.
4. The component flows that make up the overall flow development within the research combustor are in remarkable agreement with the descriptions provided by classical fluid dynamics.
5. There is no evidence that the presence of the flat optical windows and their interfacing with the corner fillets in the combustor cross-section introduce any adverse effects on the flows measured. The cross-section used provides a reasonable compromise between flow two–dimensionality and optical access.
6. The major time–mean flow features of the research combustor could be calculated by the classical integral techniques of fluid dynamics. This is somewhat surprising. However, the fluctuating velocity fields, except for a very limited initial region, are uncoupled from the time–mean features. Realistic calculation of the complete flow characteristics therefore requires the solution of transport equations.
7. Initial conditions have been established that can be used as the basis for computational fluid dynamic calculations in this combustor.

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