Velocity Field Characteristics of a Swirling Flow Combustor

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Data for reacting and nonreacting flows obtained by laser anemometry in a swirl combustor are reported and discussed. The combustor consists of two confined, concentric swirling jets. The central jet flow is premixed methane/air; the annular jet flow is air. The two flow conditions investigated are flow rotation in the same direction (coswirl) and in opposite directions (counterswirl). A closed, central recirculation zone is observed in both swirl conditions for reacting flow, but only in counterswirl for nonreacting flow. Large, anisotropic velocity fluctuations are observed in high shear regions and in the vicinity of the recirculation zone. Mechanisms for swirl-generated recirculation zone formation are discussed.

Introduction

SWIRL is imparted to flows in many practical devices including combustors and cyclone separators. It is an undesirable feature of aircraft wake flows and is observed frequently in natural flows such as tornadoes. Swirling flows exhibit a rich variety of flow features and have been the subject of research for many years. However, we still lack a complete and satisfactory understanding of these flows, and continued research is warranted. In this paper, we report the results of velocity measurements obtained in a research combustor with and without chemical reaction present. The objectives of the measurements are twofold: to investigate the influence of swirl and combustion on the combustor flowfield characteristics and to provide velocity data to assist in combustion model development and validation. These data complement data for CH_4 concentration and total number density obtained by laser-scattering techniques and reported in Refs. 1 and 2.

Even when one restricts attention to combustion, a large body of literature is found on swirling flows (see, for example, Refs. 3 and 4) and an active research community. This interest is due both to the richness of the subject and to its difficulty. At least four classes of mean flowfield can be identified in swirling flows, depending on the presence or absence of mean flow reversal in or near the vortex core: 1) no flow reversal, 2) a central recirculation zone, 3) a torrodial recirculation zone, and 4) a long backflow region or columnar flow. Class 2 includes vortex breakdown flows[5-7] and is the type of flow examined herein. Class 3 consists of those recirculation zones having a donut shape with positive mean axial velocity on the time-mean vortex centerline. This class of flow has been reported by Owen et al.[8] and others[9] and apparently is accompanied by pronounced flow oscillations, the intensity of which is much larger than one normally associates with turbulence. At high swirl levels, very long, apparently unclosed, backflow zones are observed along the vortex core.[6,10]

The flow conditions required to establish a particular flow class are not fully understood. Increasing swirl will cause a transition from class 1 to class 2 or 3 and with further swirl increases from class 2 or 3 to 4. However, the conditions that distinguish class 2 and 3 flows are not completely known. Some minimum flow Reynolds number is required for flow recirculation,[11] but the effect of Reynolds number on determining which flow class is present for flows of interest in combustion is unclear. In addition to swirl level and Reynolds number, the initial velocity profiles and flow geometry have a significant influence on swirling flows and, most likely, on the class of recirculation zone present. Further complicating the picture is the frequent occurrence of flow oscillations, as distinct from turbulence, which depend in part on the entering velocity profiles and on flow geometry. Further research is needed to establish firmly the range of flow conditions and flow geometries under which each of the different flow classes occur and to determine if other types of flow reversal occur.

There are considerable velocity data in the literature. Unfortunately, much of these were obtained with probes (e.g., Refs. 12-14) and, thus, are of questionable value. It is well known that swirling flows are sensitive to probe-induced perturbations,[7,15,16] which can be quite large. Also, when used in turbulent flows, pressure probes are subject to errors caused by turbulent fluctuations of velocity and pressure in constant density flows and of velocity, pressure, and density in variable density flows.[16] In combusting flows the influence of density fluctuations can be very significant. In light of these difficulties, it seems prudent to view probe data with skepticism unless there is evidence of little or no error in the data or until verified by other measurements.

In much of the previous experimental work, inlet flows are poorly defined and the flow geometries are complex, making these flows difficult to model and clouding the interpretation of data and the comparison of data with model calculation. Frequently, swirl vanes are located at the test section inlet insuring that individual vane wakes are present in the test section. In other cases, flow enters the test section through discrete tangential and axial flow jets that retain their identity well into the test section.[15] These jet flows may be unsteady and thus contribute to the flow oscillations so frequently observed in swirl combustors. Hub swirlers, quarrels, and sudden expansions are typical combustor and burner features which further complicate flow patterns and can be a source of flow instabilities.

The test configuration discussed in this paper was designed for a clean gometry and for well-defined inlet conditions to give a flow where turbulence and swirl are the dominant flow features. Velocities are obtained by laser anemometry and, therefore, the data are free of the doubts expressed above.

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Flow Reynolds number for all conditions studied is approximately 7.5×10^4 based on the inlet volume flow rate and the combustor diameter.

Other operating conditions are as follows. The volume average axial velocity in the inner flow (U_i) is 31.7 m/s. The ratio of volume average velocity in the inner flow to that in the outer flow is 1.4. Swirl numbers in the inner (S_i) and outer (S_o) flows as measured at the test section inlet with a five-hole pressure probe in nonreacting flow are $S_i = 0.50$ and $S_o = \pm 0.56$, where S is defined by

$$\int_{R_1}^{R_2} \tilde{U}\tilde{V}r^2 \mathrm{d}r / R_2 \int_{R_1}^{R_2} \tilde{U}^2 r \mathrm{d}r$$

with R_1 and R_2 referring to the inner and outer radii of the jet flow in question. The positive and negative signs for S_o denote co- and counterswirl. Due to optical interferences it was not possible to measure $\tilde{U}$ and $\tilde{V}$ at the inlet nor at large r. For ease of reference to previous work, S values obtained by a five-hole pressure probe are reported here. The fuel-air equivalence ratio of the inner jet $(\phi_i) = 0.84$ and the overall equivalence ratio $(\phi_a) = 0.23$, except in Figs. 10 and 11, where $\phi_i = 0.78$.

Apparatus and Instrumentation

The flow apparatus or swirl combustor (Fig. 1) is composed of confined concentric jets (5.1 cm and 10.2 cm diam.§); the inner jet flow is either air or premixed fuel and air; while the outer jet flow is air. Both flows may be swirling either in the same direction (coswirl) or in opposite directions (counterswirl). The combustor is operated at atmospheric pressure without preheat, and for these measurements is fired on methane, CH_4. The outer wall of the test section is glass and extends from the inner jet exit to approximately six outer jet diameters (D) downstream. Visual observations and measurements of temperature and composition inside and at the exit of the combustor have been made for methane-air combustion under varying flow conditions.[17-19] Beyler and Gouldin[20] have studied the reaction zone structure by measuring chemiluminescent emissions. For details of construction consult Martin et al.[17] and Martin.[21]

A single-channel laser Doppler anemometer (LDA) system operated in the dual-beam, real-fringe mode is employed to measure axial and tangential velocities in the combustor. The system consists of an argon-ion laser, Bragg cell optical frequency shifter, burst-type signal processor, and associated optical components. For these measurements, the laser is operated at 514.5 nm. The cavity is turned with an etalon for single-mode operation, and the laser power is approximately 1 W.

The measurement volume formed by the laser beams' intersection is approximately ellipsoidal in shape with major and minor axes 2.7 mm and 0.19 mm long; fringe spacing in the volume is 2.6 μm. Scattered radiation from the measurement volume is collected in the near-forward scatter direction and detected by a photomultiplier tube. Integral with the photomultiplier tube housing is a preamplifier; stated bandwidth for the combination of tube and amplifier is 100 MHz. A pinhole in front of the photomultiplier tube acts as a spatial filter to give an effective measurement volume of approximately 0.5×0.2 mm. The entire LDA optical system is mounted on a traversing mechanism which provides for horizontal movement of the measurement volume across the combustor diameter and a distance $6D$ in the axial direction.

The Doppler signal processor is a burst or counter type with 1 ns temporal resolution. The digital output from the processor is transferred via a buffer circuit to a laboratory computer for data storage and analyses. Shifting of the frequency of one laser beam with respect to that of the other allows for the determination of fluid motion direction as well as speed; the frequency shift is 40 MHz. Finally, the laser beam focusing optics are rotated to measure both axial and tangential velocities.

The cylindrical combustor walls are glass, and the entering laser beams suffer refraction which affects the measurement volume location. Reported data are corrected for this effect. In addition, laser beam reflections from the wall make it impossible to focus the collection optics adequately when the measurement volume is near a wall, and the resulting deterioration in the signal-to-noise ratio precludes the determination of velocity in the vicinity of the wall.

Both inner and outer jet flows are seeded to low concentrations aluminum oxide particles with nominal diameters of 1.0 μm or less supplied from a fluidized bed seeding system. A nearly uniform seed level in both jet flows is achieved by injecting the seed at the exit of the centrifugal blower which supplies both flows. A low seed level, and therefore a low data rate, is used to avoid problems with agglomeration and nonuniformity in seed distribution associated with high seeding levels. The average LDA data rate in cold flow is approximately 400/min throughout the test section which implies a uniform seed distribution. With combustion the data rate is reduced and varies in time and space due to variation in seed concentration with gas density. This influence on data rate is called density bias. If the seed distribution in the flow entering the test section is statistically uniform and seed particle slip relative to the gas is negligible, seed density is proportional to gas density, and this bias leads to density-weighted or Favre-averaged results.[22,23] Therefore, we conclude that our results for mean and rms velocity with density bias are good estimates of the corresponding Favre quantity.

Data are reported for Favre mean and rms fluctuations of axial and tangential velocity in the combustor under different operating conditions. Data sets of 1000 velocity realizations for isothermal flow and 500 realizations for combusting flow are analyzed for these quantities. For the isothermal flow measurements the signal processor is operated in the N-cycle mode; the period for eight cycles is timed to find the Doppler frequency. With these data no velocity bias correction is made. However, the bias due to varying flow direction relative to the measurement volume is virtually eliminated by the 40 MHz frequency shift. The total burst mode of signal analysis is used in the reacting flow cases, and velocity bias corrections are made as suggested by Buchhave et al.[24] To evaluate the influence of velocity bias in the isothermal flow data, additional isothermal velocity measurements were made

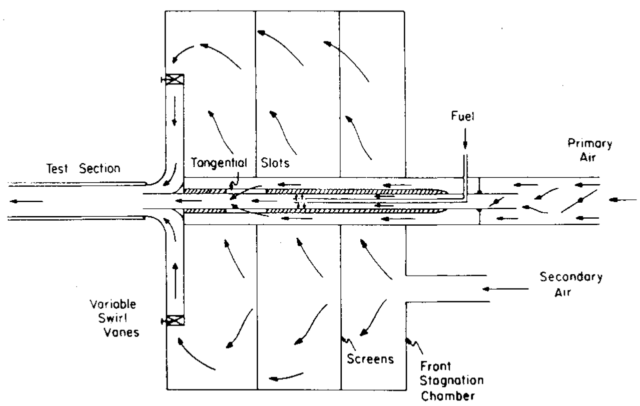

Fig. 1 Schematic of apparatus showing test section and swirl-generating assemblies. The outer flow swirl vanes are symmetric in shape, and in these measurements, their cords made angles of ±55 deg w.r.t. the radii passing through their pivot points. Inner flow swirl is obtained by a combination of axial and tangential flow injection as indicated. Fuel is injected 5*D* from the test section inlet.

§The inner jet enters the test section through a 5.1 cm outer diameter tube of 1.5 mm wall thickness.

using the total burst mode.[25] From these data it is concluded that, for the conditions studied, velocity bias is unimportant in the mean velocities, of minor importance in the rms velocities, and repeating the isothermal flow measurements is not warranted.

As a check on the LDA system performance, velocity measurements were performed in nonswirling flows, and the results for the mean and rms velocities were compared to hot-film data for the same flow. Over a range of mean velocities comparable to that expected in the combustor, the mean velocities obtained with the two techniques were within a few percent of each other. Differences of up to 20% in rms levels were observed for turbulent intensities up to 7%. Such discrepancies in the rms are to be expected in these measurements.[27,28] A further check of LDA performance for isothermal flows can be obtained by integrating the axial velocity profiles across the test section to obtain the total volume flow rate. However, as explained above it is not possible to measure in the vicinity of the wall, and therefore such a check is not feasible in the present case.

Results

The primary results reported herein are radial profiles of estimated Favre mean velocity ($\tilde{U}, \tilde{V}$) and of estimated Favre rms velocity fluctuations ($\tilde{u},\tilde{v}$) for the axial and tangential velocity components under four operating conditions—coswirl and counterswirl for both hot and cold flow. The data are presented in Figs. 2-9. In addition, centerline profiles of mean and rms axial velocity are presented in Figs. 10 and 11. The velocity data from several test cases exhibited a high degree of axial symmetry, and hence only radial profiles were obtained.

For three of the four flow conditions, a stable central recirculation zone of finite length is observed in the vortex core. In the three flows with recirculation the flow downstream of the recirculation bubble[¶] is positive, and turbulent fluctuations, although high in and around the recirculation zone and in the interjet shear layer for counterswirl, decay to relatively low values at large X/D. At large X/D, the axial velocity profiles are relatively flat except for the combusting coswirl case where a fast, hot core flow is evident.

A most surprising result of these measurements is the presence of a recirculation bubble for coswirl with combustion when there is none without combustion. Mass conservation requires axial flow acceleration with combustion, and therefore a favorable pressure gradient must exist over a portion of the test section. Since the formation of a central recirculation zone requires an adverse pressure gradient on the centerline, one would expect combustion to have an adverse, not a positive, influence on bubble formation. This apparent contradiction will be discussed further in the next section.

Regarding the tangential velocity profiles (Figs. 5 and 9), one observes much higher velocities in the forward portion of the bubble for cold flow when compared to the hot flow with counterswirl. (Of course, no such comparison is possible in the coswirl cases.) Since the recirculation zone is confined to the center of the vortex core, one expects the fluid entering the bubble (e.g., by turbulent diffusion across the bounding streamline) to have little or no tangential velocity resulting in low tangential velocities in the bubble as is seen in several works[5,26,29] as well as in the present hot flow results. However, in other experiments[30] and for the present cold flow results, measurable swirl velocities are observed in the recirculation zone. At the present time we believe that these differences reflect differences in radial, momentum transport by turbulent and viscous mechanisms. Also, we note that mean tangential velocities are not always zero on the centerline, indicating some, slight flow asymmetry.

¶The phrases "recirculation zone" and "recirculation bubble" are used interchangeably; both refer to the entire volume of fluid bounded by the mean flow, zero stream surface.

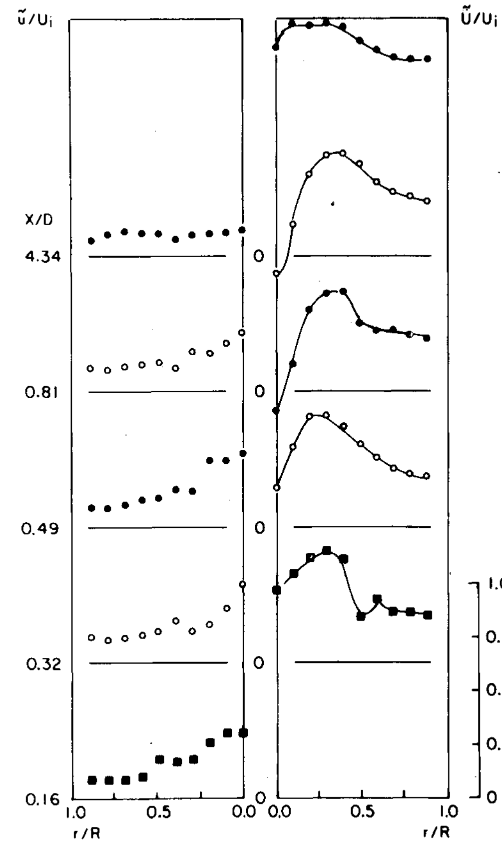

Fig. 2 Axial velocity data for cold with coswirl at five axial stations; $X/D = 0.16$ (■), 0.32 (○), 0.49 (●), 0.81 (○), and 4.34 (●). R is the combustor radius. The velocity scale is the same for $\tilde{u}/U_i$ and $\tilde{U}/U_i$ and shown on lower right.

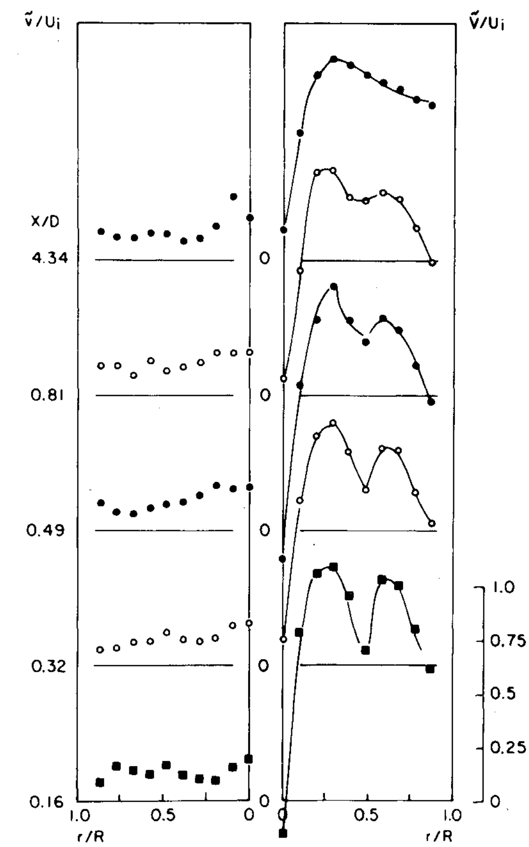

Fig. 3 Tangential velocity data for cold flow with coswirl at the same five axial stations as in Fig. 2; $X/D = 0.16$ (■), 0.32 (○), 0.49 (●), 0.81 (○), and 4.34 (●). Velocity scale shown on lower right.

There are other, rather small, differences in mean flow characteristics between the cold and reacting flow cases for counterswirl, the most notable of which is the higher axial velocities around the recirculation zone with reaction (Figs. 4 and 8). The higher values lie in the region of major chemical heat release as determined by optical measurements.[20] Thus, the observed acceleration appears to be that necessary to satisfy mass conservation.

For counterswirl the location of the shear layer between the two jets is clearly seen in the tangential velocity profiles, both mean and rms (Figs. 5 and 9). From these data it is clear that the recirculation bubble is embedded in the vortex core of the central jet and shielded by the central jet from the outer flow. Also, the tangential velocity data indicate that the interjet shear layer is not forced to significantly larger radii in the combusting flow, relative to the cold flow, by expansion of hot combustion products. Overall, the changes observed for the counterswirl case in going from cold to hot flow are not unexpected and are consistent with previous measurements.[12,30,31]

Regarding the turbulence data, first consider the results for counterswirl. In both hot and cold flows pronounced peaks in $\tilde{u}$ (Figs. 4 and 8) are observed near the edge but apparently outside the recirculation zone, while local maxima in $\tilde{v}$ are observed in the recirculation zone and in the mixing layer between the two jets (Figs. 5 and 9). In the upstream portion of mixing layer $\tilde{v}/\tilde{u} \simeq 2$, which is high for free shear layers but not unusual in boundary layers. Comparable values ($\simeq 2$) for $\tilde{u}/\tilde{v}$ are seen in the recirculation bubble boundary layer. The peak in $\tilde{u}$ at $X/D = 0.157$ and $r/R \simeq 0.5$ (Fig. 8) is the wake of the tube wall separating the two jets before they enter the test section.

Peak $\tilde{u}$ values clearly fall outside the recirculation zone over approximately the forward half of the bubble but over the aft portion the peaks fall on or very near the bubble boundary. $\tilde{u}$ values in this region are comparable for both hot and cold flows, which is surprising since this is the region of chemical reaction and of high shear in the reacting flow case. Furthermore, high values of $\tilde{v}$ in the recirculation zone are somewhat surprising. Both observations may reflect unsteadiness in the recirculation bubble position, which contributes to measured rms levels. Recently obtained density fluctuation data[1,2] support this hypothesis.

The coswirl turbulence data exhibit less structure and more apparent scatter in part because there is no large peak in $\tilde{v}$ in the interjet shear layer. Furthermore, there is no recirculation zone in cold flow with its accompanying boundary layer and sources of fluctuations.

For coswirl in cold flow, large values of $\tilde{u}$ and $\tilde{v}$ (Figs. 2 and 3) are measured in the vicinity of the centerline which is a region of mean velocity shear and turbulence generation. With combustion a recirculation zone and boundary-layer flow are seen accompanied by local maxima in $\tilde{u}$ (Fig. 6) as is expected. However, when comparison is made with the counterswirl results one sees that the $\tilde{u}$ maxima occur at higher $\bar{U}$ (larger radius) in counterswirl than in coswirl. We suspect that fluctuations of the recirculation zone position may be contributing to $\tilde{u}$ and $\tilde{v}$ to a greater extent in this region for coswirl as opposed to counterswirl.

The $\tilde{u}$ data in Fig. 6 also exhibit unexpected peaks at large r/R; they are observed at all axial locations and at more than one radial location. Velocity histograms of U, the instantaneous velocity, at these points are bimodal indicating intermittency in the flow possibly related to an instability in the wall boundary layer. More work is needed to explain these observations.

Since the hot-flow data contain density bias our comparisons between hot and cold flow should be viewed with

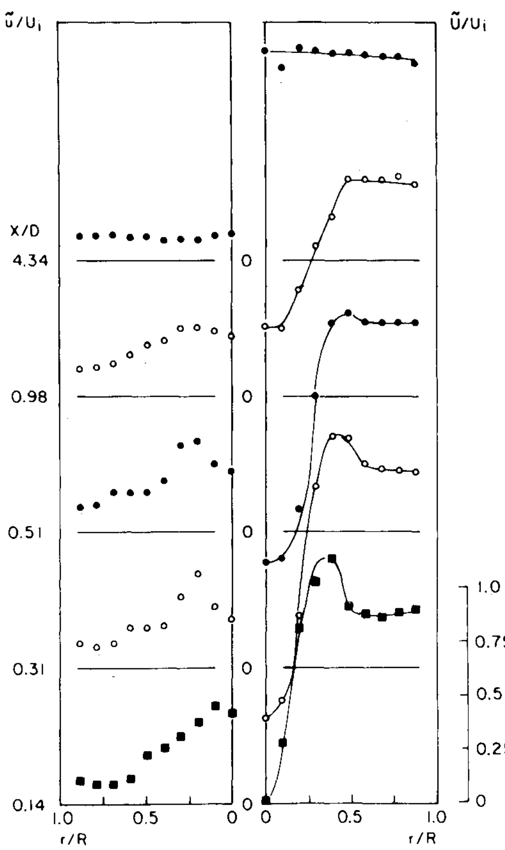

Fig. 4 Axial velocity data for cold flow with counterswirl; $X/D = 0.14$ (■), 0.31 (○), 0.51 (●), 0.98 (○), and 4.34 (●). Velocity scale shown on lower right.

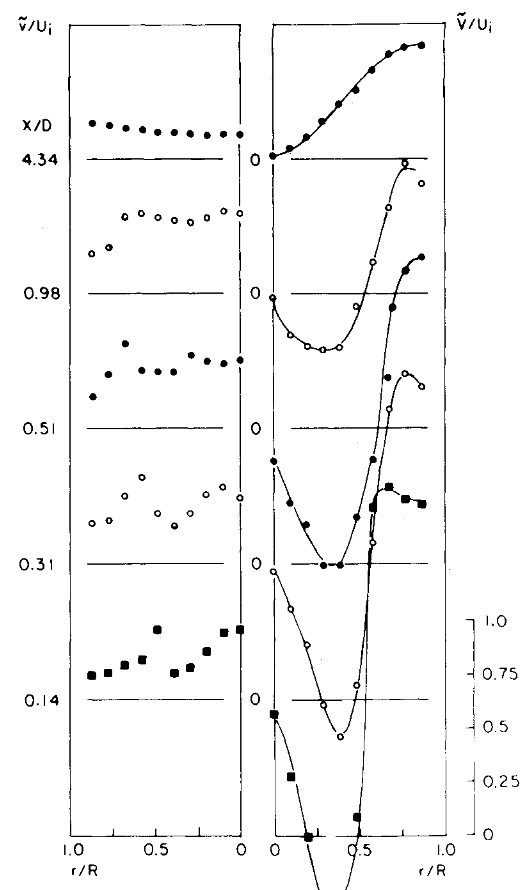

Fig. 5 Tangential velocity data for cold flow with counterswirl; $X/D = 0.14$ (■), 0.31 (○), 0.51 (●), 0.98 (○), and 4.34 (●). Velocity scale shown on lower right.

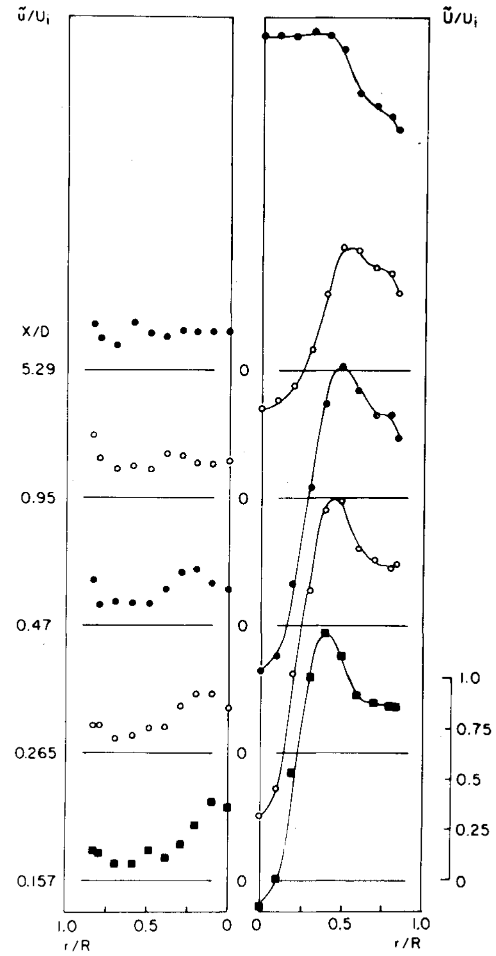

Fig. 6 Axial velocity data for combusting flow with coswirl; $X/D = 0.167$ (■), 0.265 (○), 0.47 (●), 0.95 (○), and 5.29 (●). Velocity scale shown on lower right.

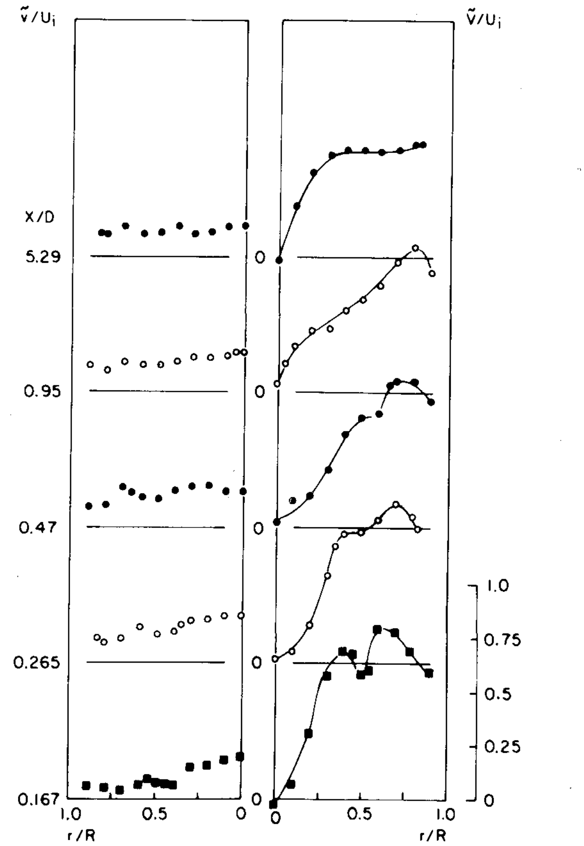

Fig. 7 Tangential velocity data for combusting flow with coswirl; $X/D = 0.167$ (■), 0.265 (○), 0.47 (●), 0.95 (○), and 5.29 (●). Velocity scale shown on lower right.

caution. Consider the rms measurements. In cold flow we measure $\tilde{u} \simeq [\overline{(U-\bar{U})^2}]^{1/2}$, while in hot flow $\tilde{u} \simeq [(\overline{\rho U^2}/\bar{\rho}) - \tilde{U}^2]^{1/2}$. Clearly, density fluctuations complicate comparisons between hot and cold flow results.

Discussion

The most interesting result of our measurements is the observation of flow recirculation for coswirl with combustion but no recirculation without combustion. An explanation of this observation requires a discussion of the mechanism(s) for flow reversal.

Sufficiently far upstream of the recirculation zone but still in a region of adverse pressure gradient, the mean flow may be considered quasicylindrical,[32] and the radial momentum equation can be integrated to obtain[26]

$$\frac{\partial \bar{P}}{\partial x}_{r=0} = \frac{\partial \bar{P}}{\partial x}_{r=R} + \frac{\partial}{\partial x}\int_0^R \frac{\bar{\rho}\tilde{V}^2}{r}\,\mathrm{d}r \qquad (1)$$

where turbulence and viscous stresses are neglected, the overbar denotes mean quantities, and R is the test section radius. Pressure measurements of Vu and Gouldin[26] for incompressible flow in an apparatus of nearly similar geometry show that $(\partial\bar{P}/\partial x)_{r=R} < 0$ but of small magnitude. With reaction, we expect $(\partial\bar{P}/\partial x)_{r=R}$ to be either unchanged or more favorable. Thus for flow reversal,

$$\frac{\partial}{\partial x}\int_0^R \frac{\bar{\rho}\tilde{V}^2}{r}\,\mathrm{d}r$$

must be sufficiently positive to overcome the negative $\partial\bar{P}/\partial x$ contribution at the wall and the dynamic head of the axial flow.

In explanation of flow reversal, it is frequently suggested that the required evolution of the integral in Eq. (1) results from turbulent momentum transport (or viscous transport in laminar flow).[15] However, in the present case, this hypothesis appears invalid for a number of reasons. It is doubtful that a dissipative process can produce the rapid, precipitous drop in centerline axial velocity upstream of the recirculation zone which is apparent in the data of Fig. 10. Similar explanations have been offered for recirculation in laminar, swirling flows without success.[6,7] Finally, in view of the high Reynolds number of these flows, turbulent momentum transport is not significant except in regions of high turbulence intensity and large mean velocity shear, qualities which do not characterize the flow *approaching* the recirculation zone. Thus we conclude that turbulent transport is not the mechanism for swirl-induced recirculation in our flows and that, most likely, it is not the cause of flow recirculation in most turbulent, swirling flows. Gore and Ranz reach a similar conclusion for swirling flows with expanding cross sections.[15]

Gupta[9] has suggested that, for high Reynolds number flow, oscillations such as the processing vortex core are important to the mechanism for flow reversal. We believe that such a hypothesis is not applicable to the present results since, in our opinion, the flows examined do not exhibit the large amplitude oscillations cited by Gupta.

To explore additional mechanisms for flow reversal, we introduce Bernoulli's equation and an expression for circulation. We assume an axisymmetric, stationary, constant density flow and neglect viscous and turbulent stresses. The neglect of the stress terms is justified since we seek an explanation for flow reversal independent of these effects, while the constant density assumption is valid upstream of the

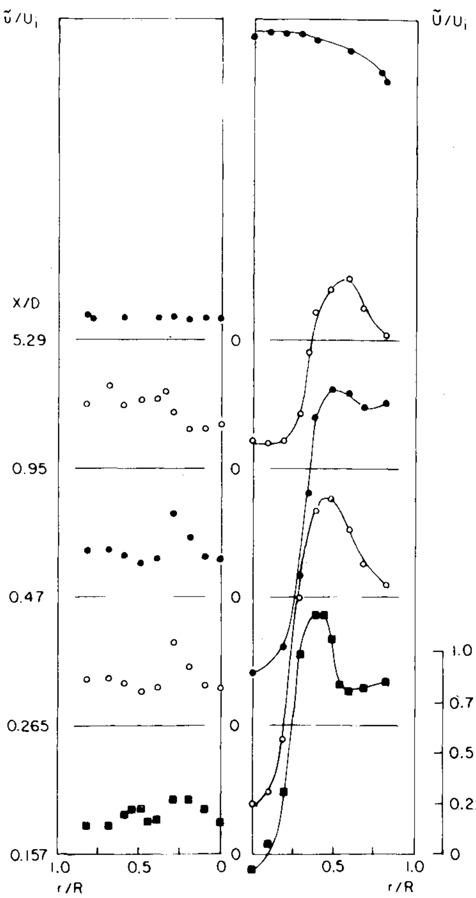

Fig. 8 Axial velocity data for combusting flow with counterswirl; $X/D = 0.157$ (■), 0.265 (○), 0.47 (●), 0.95 (○), and 5.29 (●). Velocity scale shown on lower right.

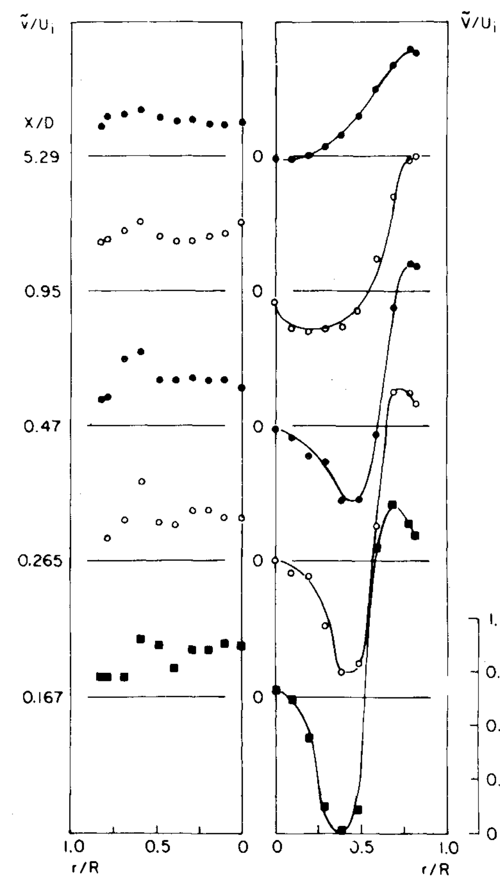

Fig. 9 Tangential velocity data for combusting flow with counterswirl; $X/D = 0.167$ (■), 0.265 (○), 0.47 (●), 0.95 (○), and 5.29 (●). Velocity scale shown on lower right.

reaction zone where our attention is now focused. (Flame emission measurements[20] show that reaction begins at the entrance to the test section slightly upstream of the recirculation zone.) In this case mean flow circulation is preserved and a Bernoulli-like equation for mean flow can be obtained.

$$\tfrac{1}{2}(\tilde{U}^2 + \tilde{V}^2 + \tilde{W}^2) + \bar{P}/\rho = H(\bar{\psi}) \tag{2}$$

$$r\tilde{V} = C(\bar{\psi}) \tag{3}$$

The Bernoulli constant H and the circulation C are functions of $\bar{\psi}$, the meanstream function. Meanstream surfaces are surfaces of revolution.

Equations (2) and (3) are good for axisymmetric flows, and when further specialized to quasicylindrical flows they can be solved[32] to show that streamtube divergence will intensify on the vortex centerline an imposed (on the vortex core) adverse pressure gradient. This may be seen from the radial momentum equation, which for the assumed flow conditions, is

$$\frac{1}{\rho}\frac{\partial \bar{P}}{\partial r} = \frac{C^2}{r^3} \tag{4}$$

With C a monatonic increasing function of $\bar{\psi}$, it is seen that streamtube expansion gives reduced $\partial \bar{P}/\partial r$ and higher pressure on the centerline. Thus, with rapid flow expansion a recirculation zone can be established on the centerline in a flow with sufficiently high-swirl levels; a similar conclusion is reached in Ref. 15. Many combustor and burner designs feature sudden expansions and for these no additional

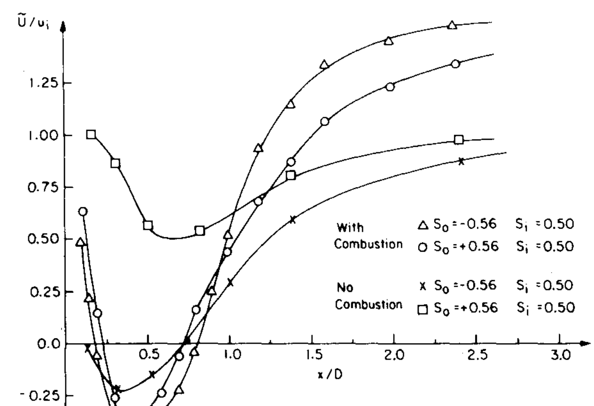

Fig. 10 Centerline profiles of Favre mean axial velocities for cold and combusting flows. Negative S_0 indicates counterswirl conditions, ϕ_i for hot flow data is 0.78.

mechanism appears necessary to explain flow reversal. However, for the present combustor configuration and for similar combustor and burner configurations, there is no obvious reason for streamtube expansion in the vortex core, and additional mechanisms must be explored.

Vortex breakdown flows have been identified and studied in a variety of flow configurations both at modest and high Reynolds number.[6,7,11] In reviews both Hall[7] and Leibovich[6] cite swirling, combusting flows with recirculation bubbles as examples of vortex breakdown. On the other hand, Gupta[9] and Syred and Beer[33] consider vortex breakdown to be 1) a low Reynolds number precursor of the reverse flows found in practical devices, and 2) a transitional flow marking the change from precessing vortex flows to damped PVC flows. In either case, breakdown flows are considered to be of little interest to practical devices. We disagree with this position that vortex breakdown is of limited practical interest. Indeed we believe our flows are examples of vortex breakdown in high Reynolds number combusting flows.

The most satisfactory explanation for vortex breakdown thus far proposed is that of Benjamin[34,35] who associates vortex breakdown with a transition in flowfield character and with the presence of standing waves. The transition is between an upstream supercritical region into which axisymmetric waves cannot propagate and a downstream subcritical region through which axisymmetric waves can propagate. In the transition or transcritical region, waves propagating from downstream accumulate to form a vortex breakdown. For laminar flow Randall and Leibovich[36] have modeled the bubble form of vortex breakdown as a standing, axisymmetric trapped wave. We hypothesize that this wave mechanism is the cause of recirculation zone formation in a number of (but not all) swirling flow combustors, including the one we have studied.

Applying these ideas to our coswirling flow results, we argue that without reaction the flow is supercritical in the test section. Combustion is initiated by a spark ignitor with long electrodes penetrating the test section to the centerline. Initially, combustion is stabilized in the electrode wakes, but when they are withdrawn the flame remains stabilized by a central recirculation zone. Combustion affects the flow sufficiently to cause a transition from supercritical to transcritical flow, thereby allowing a vortex breakdown to form. In the hot products the flow is subcritical.

An alternate explanation for flow recirculation with combustion is that combustion alone causes sufficient streamtube expansion to generate the necessary adverse pressure gradient leading to flow reversal. This explanation is not appealing because it introduces yet another mechanism for flow reversal, one valid only in reacting flows. We conclude that vortex breakdown provides the best explanation for the reverse flows we observe. At the same time we should point out that such an explanation is not necessary in sudden expansion geometries and that it may not be applicable to flows exhibiting significant flow instabilities.

In this discussion, the absence of pervasive, large-scale, high-energy oscillations has been emphasized in part to distinguish the present flows from those containing energetic precessing vortex cores or other large, high-energy oscillations such as the flows studied by Owen et al.[8] On the other hand, from visual observations and density measurements, it is apparent that the recirculation bubble undergoes oscillations in the axial direction. In the velocity data one also finds evidence for such oscillations. Local maxima in $\tilde{u}$ on the centerline near the forward and rear stagnation points (Fig. 11) are seen. Velocity histograms are bimodal in the vicinity of the forward stagnation point but not near the rear stagnation point. Correspondingly, the $\tilde{u}$ levels are much higher around the forward stagnation point. It seems that at least the front end of the recirculation bubble is oscillating in the axial direction and that these oscillations are contributing to the high $\tilde{u}$ measured in this region, while near the rear stagnation point $\tilde{u}$ is lower, indicating that bubble oscillations make a smaller contribution to $\tilde{u}$ there than in the front. As noted above, these oscillations in bubble position may also contribute to $\tilde{u}$ and $\tilde{v}$ at other locations in and near the bubble.

In addition to bubble oscillations, the density data indicate the presence of moderate frequency oscillations (400-500 Hz) which originate in the inner flow upstream of the recirculation zone. These periodic oscillations are attributed to helical waves triggered by hydrodynamic instability in the upstream flow.[2]

Clearly, flow oscillations that may usefully be distinguished from the more random fluctuations of turbulence are present

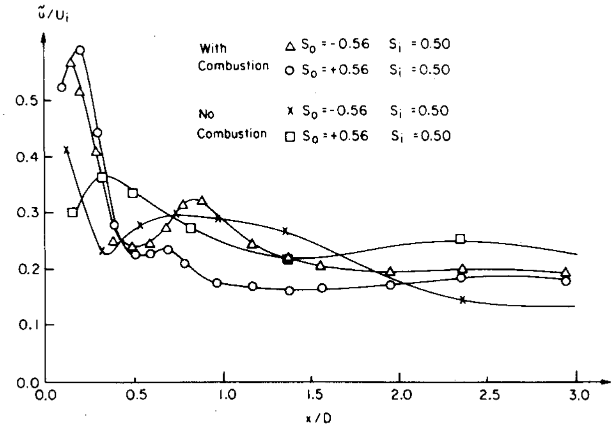

Fig. 11 Centerline profiles of Favre rms axial velocity for the same conditions as Fig. 10.

in our flows, and in certain regions they make significant contributions to measured rms fluctuations.

Our measurements were conducted over a three-year period (cold-flow followed by hot-flow measurements), and the repeatability of flow conditions is a concern. Measurements show that the reproducibility of cold-flow conditions is good. For selected test runs centerline axial velocities are quite repeatable, while the maximum difference seen in radial profiles is less than 10%. On the other hand, our experience indicates that these flows are quite sensitive to inlet conditions and to fuel-air ratio making exact duplication a tedious process. Slight changes in flow conditions can result in a marked change of the flow. For example, centerline axial velocity profiles have been obtained for two equivalence ratios: $\phi_i = 0.78$ and 0.84 in the inner jet. With the higher ϕ_i the front stagnation point of the recirculation bubble moves forward by almost 1 cm relative to that for the lower ϕ_i. This sensitivity underscores the complexity of these flows and the difficulties faced by the experimentalist and by those who would predict these flows through modeling and analysis.

Concluding Remarks

The data presented in this paper have important implications for flow modeling and calculation. The observed sensitivity to inlet and boundary conditions implies that accurate boundary conditions must be used for calculations, and there is the danger that incorrect boundary or inlet conditions can result in apparently accurate flow calculations. There is more than one mechanism for flow recirculation, and a flow prediction model that works for one flow geometry or one class of flows may not work for others. In many cases, recirculation zone formation is an inviscid flow process only indirectly influenced by viscous and turbulent momentum transport. Thus the failure to accurately predict flow recirculation is most likely *not* the result of a poor turbulence model. On the other hand, waves and flow oscillation are frequently linked to flow recirculation, and it may prove necessary to incorporate explicitly their influence into models for such flows.

The influence of turbulence and turbulent transport on flow recirculation should not be discounted entirely. Flow patterns in and around the recirculation zone are affected by turbulence as is flow in the mixing layer between the inner and outer jets. These effects may in turn influence flow recirculation; for example, turbulence accelerates combustion which clearly can affect recirculation zone formation. Finally, we note, as is well known, that swirl affects turbulence levels and turbulent transport. The effect is greatly magnified in variable density flows where, depending on conditions, turbulence production can be either enhanced or suppressed by swirl.

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