Behaviour of carbon dioxide jets in a confined swirling flow

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An investigation of jet mixing in confined swirling flow, using carbon dioxide as the jet fluid, was carried out. In order to compare the present results with previous measurements by So *et al*[1] on homogeneous and helium jet mixing, the experiments were carried out in the same facility and under the same test conditions. Contrary to the flow characteristics found in helium jet mixing in confined swirling flow, density difference and swirl combined to give rise to an accelerated decay of the jet and increased mixing between jet and swirling air. Consequently, the second reversed flow region observed in the swirling flow was only slightly displaced downstream. This contrasted with a radial displacement of the second reversed flow region by the helium jets and a complete destruction of the reversed flow regions by the air jets.

Keywords: *swirling flow, confined jets, inhomogeneous flows, turbulent mixing, carbon dioxide jets*

Introduction

Annular gas turbine combustors are designed to give complete combustion between fuel and oxidant in the shortest possible distance and uniform velocity and temperature distributions at the exit of the combustor. To achieve these objectives, the liquid fuel is atomized and thoroughly mixed with air before injecting into the combustor. Secondary air jets are used to deliver more air for mixing and complete burning. Both the fuel–air and the secondary air jets can be swirling or nonswirling. Also, the swirling can be in the same direction or counter to each other. It is believed that through the creation of a recirculation region in the flow field, and the anchoring of the flame in this region, complete combustion can be achieved efficiently. Further downstream, dilution air is injected into the combustor to burn off unburnt fuel, to lower the gas temperature and above all to thoroughly mix the gases and give uniform distributions of velocity and temperature at the combustor exit. This last requirement is of utmost importance because a nonuniformity of 50°F in the temperature distribution will decrease the life of the first stage turbine blades significantly[2]. It is also found that the dilution air jets are crucial to the attainment of uniform temperature distribution in a relatively short combustor. Without them, the flow and temperature fields at the combustor exit are nonuniform. The reason for this is not clear. It could be due to insufficient length for mixing, or to confinement of hot combustion products by relatively cool swirling air. Therefore, the phenomenon resulting from the mixing of a swirling or nonswirling gas with a swirling external gas of different density is of great interest to combustor designers.

Variable-density coaxial jet mixing with and without swirl has been studied by a number of researchers[3-10]. Homogeneous mixing was reported by Habib and Whitelaw[3,4], Vu and Gouldin[5] and Johnson and Bennett[6]. The effect, on coaxial jet mixing, of swirling only the annular stream was investigated in detail by Habib and Whitelaw[3,4]. In their studies, the coaxial jets were discharged into a confinement whose area ratio was about 8 times that of the annular jet. They found that swirl was effective in destroying the recirculation region commonly found in sudden expansion flows, thus indicating that mixing was promoted by swirl and the region of swirl influence extended far beyond the jet mixing regions. Vu and Gouldin[5] studied the effects of swirling both streams on jet mixing. The two streams were either swirling in the same direction or in opposite directions. Their results showed that swirling the annular stream had strong effects on the formation of a recirculation zone and mixing in the shear interface. As the outer swirl number was decreased from counter-swirl to co-swirl conditions, the size of the recirculation zone diminished, and so did the reversed flow velocities. Also, stronger turbulence was found in the interface under counter-swirl conditions than co-swirl conditions. On the other hand mass transfer in the form of a passive scalar was examined by Johnson and Bennett[6]. A major finding of their investigation was the discovery of a region of counter-gradient turbulent axial mass transport. It occurred in the region where the annular jet fluid was accelerating the central jet fluid. Inhomogeneous mixing without swirl was examined by Zakkay *et al*[7], Alpinieri[8], Chriss[9] and Abramovich *et al*[10]. These studies covered heated jets as well as jets of hydrogen, carbon dioxide, and freon mixing with air. Situations investigated ranged from that of central jet density lighter than annular jet density to that of the reverse case. Among the major findings were the effects of jet density and velocity ratios on the central jet potential core and the decay of centreline velocity and density. In spite of all these detailed studies on coaxial jet mixing, the question of swirl effects on variable density jet mixing has not been properly addressed. Therefore, further study in this area is required, if the fluid dynamics of mixing in combustors is to be understood.

An experimental programme on isothermal mixing of gas jets in confined swirling air flow was initiated at Arizona State University some four years ago. The primary objective of the programme is to seek understanding of the complex phenomena found in jet mixing in gas turbine combustors. Since then, velocity and gas concentration characteristics related to isothermal, homogeneous and light gas mixing in confined swirling flow have been reported[1,11-13]. In the study reported here, the mixing behaviour of carbon dioxide jets in a confined swirling air flow was examined. With this investigation, a fairly complete understanding of the density effects on jet mixing in confined swirling flows can be achieved.

The present experiments were carried out in the same test facility as that used in Ref 1. Therefore, only a brief description of the facility is given in the following section for completeness' sake. The experimental conditions and results are outlined in the third section, while a thorough discussion and comparison of the present and previous results are given in the fourth section. Finally, the conclusions are summarized.

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Test facility and instrumentation

The test facility and instrumentation used in the present experiments were identical to those described in Refs 1 and 11–13. Essentially, the test rig consisted of a jet nozzle arranged concentrically within a constant-angle vane swirler that generated a swirling flow characterized by a swirl number $S = 2.25$. The swirl only decayed slightly in the test section of the test rig. The jet nozzle diameter D_j was 8.73 mm, and the swirler outer diameter was 125 mm. This nozzle/swirler arrangement was mounted concentrically into a Plexiglas tube of length 0.76 m (or six tube diameters) and formed part of the test section of an open-jet wind tunnel powered by a 25 HP variable speed motor that drove a blower directly (Fig 1). The flow upstream of the swirler was fully turbulent with a uniform velocity profile across approximately 80% of the tube and a uniform turbulence intensity of about 5.5%. Therefore, *Re* based on tube diameter and averaged tube velcoity was 5.5×10^4. All experiments were carried out at this one Reynolds number, which is identical to that in Ref 1. Carbon dioxide from compressed gas bottles was supplied to the jet nozzle via a heat exchanger to warm up the gas to room temperature so that isothermal flow (to within ± 1°F of the air temperature) through the test section could be set up. Jet flows through the nozzle were made fully turbulent by designing the nozzle with a sudden expansion in accordance with the suggestion of Ref 1. Both the jet flow and the swirling flow were fully turbulent so that all flows tested were independent of Reynolds number effects.

A standard DISA Model 55L laser Doppler anemometer (LDA) equipped with a DISA 55N10 frequency shifter operating in the forward scatter mode was used to measure the instantaneous axial and circumferential velocities, u and w. The diagnostic technique and data reduction procedure were the same as those discussed in Ref 1. For carbon dioxide jet experiments, it was found that seeding the flow upstream of the swirler only was sufficient to give high quality signals for processing. Therefore, the experiments were carried out by seeding the flow with glycerine–water droplets, of mean size around 1 μm. These droplets were generated by a DISA 55L18 seeding generator. This technique was found to be satisfactory since the measured U did not vary if the carbon dioxide jets were also seeded. The jet velocity was determined using a rotormeter calibrated for carbon dioxide gas. Further details about the test facility and diagnostic technique can be found in Ref 1.

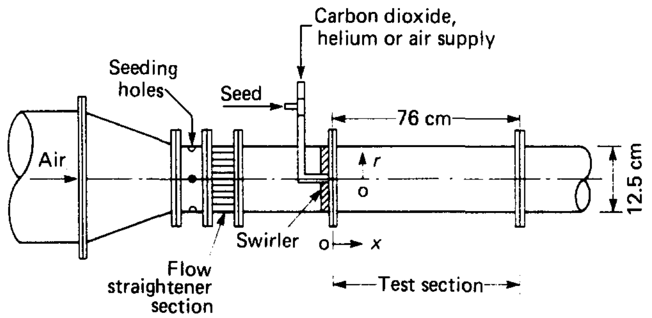

Figure 1 Schematic diagram of test rig

Test conditions and results

In order to compare the present results with those reported in Refs 1, 11 and 12, similar test conditions were selected. These conditions are summarized in Table 1.

The parameters ρ_j/ρ_a, U_j, Re_j and $\dot{M}_j/\dot{M}$ denote jet fluid to swirling air density ratio, jet velocity, Reynolds number based on U_j and jet nozzle diameter, and jet to swirling flow axial momentum ratio, respectively. Therefore, the gas jet experiments carried out to date cover a wide range of density and momentum ratios, and provide sufficient data to facilitate a fair understanding of isothermal, turbulent gas jet mixing in confined swirling air flows.

The wall static pressure distribution along the first eight tube diameters downstream of the jet was measured in addition to the profiles of u and w at selected x/D_j locations. A comparison of the velocity measurements is presented in the next section. As for the pressure measurements, it is enough to note that pressure drop behaviour in the first eight tube diameters was linear and was essentially dominated by the swirling motion. The slope of

Table 1 Test conditions of gas jet experiments

Parameters	Carbon dioxide jet		Air jet[1,11]			Helium/air jet[1,12]	
ρ_j/ρ_a	1.52	1.52	1	1	1	0.31	0.23
U_j (m/s)	25.4	54.0	25.4	66.8	152.8	16.8	36.5
$Re_j \times 10^{-3}$	28.43	60.44	14.38	37.82	83.51	1.50	2.97
$\dot{M}_j/\dot{M}$	0.104	0.472	0.068	0.475	2.48	0.009	0.032

Notation

- D Diameter of tube or jet
- $\dot{M}$ Axial momentum flux of swirling flow $\equiv \int_0^R 2\pi U^2 r\,\mathrm{d}r$
- $\dot{M}_j$ Jet momentum flux $\equiv \frac{1}{4}\pi D_j^2 U_j^2$
- r Radial coordinate
- R Radius of tube
- Re Reynolds number based on tube or jet diameter
- S Swirl number $\equiv \dfrac{\int_0^R WUr^2\,\mathrm{d}r}{R\int_0^R U^2 r\,\mathrm{d}r} \approx \tan\theta$
- u Instantaneous axial velocity
- u' rms of fluctuating u velocity
- U Mean axial velocity
- $\bar{U}$ Average U velocity at any x location $\equiv \dfrac{1}{R^2}\int_0^R 2Ur\,\mathrm{d}r$
- U_{av} Overall average U velocity upstream of swirler $= 6.8$ m/s
- W Mean circumferential velocity
- w Instantaneous circumferential velocity
- w' rms of fluctuating w velocity
- x Axial coordinate measured from jet exit
- ρ Density of fluid
- θ Vane angle of swirler $= 66°$

Subscripts

- a Air
- j Jet
- o Centreline

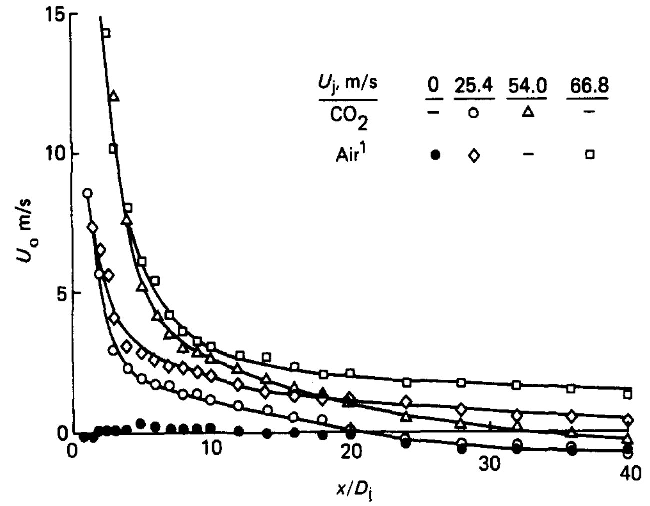

Figure 2 Decay of centreline mean axial velocity

the pressure drop curves was approximately the same for carbon dioxide, air, and helium/air jets. Increasing the jet velocity affected the level of the pressure drop; however, the slope remained practically unchanged. Therefore, the axial pressure drop behaviour is not an important parameter in the flow under investigation, and the parameters of importance are ρ_j/ρ_a, U_j and $\dot{M}_j/\dot{M}$ at a fixed swirl number $S=2.25$.

Continuity checks were carried out on the measured $U(r)$ at different x/D_j locations in accordance with the suggestion of Ref 1. The results show that continuity is satisfied to within $\pm 8\%$, which is approximately the same as the variations noted in the blower's discharge[1]. Consequently, all $U(r)$ presentations are made with $U(r)/\bar{U}$ versus r/R. This presentation allows the continuity equation to be satisfied at any location in the test section. On the other hand, $W(r)$ presentations are made with $W(r)/U_{av}$ versus r/R, because it is immaterial as to which characteristic velocity is used to normalize W as long as it is constant.

Flow field comparison

Centreline decay behaviour

The centreline velocities $U_o(x)$ for the carbon dioxide and air jets and for the $U_j=0$ case are plotted in Fig 2. It can be seen that, for pure swirling flow, two reversed flow regions are detected: one is at $0<x/D_j<3$, and another starts at $x/D_j\approx 15$ and extends to $x/D_j>40$. These reversed flow regions are created because of the swirling motion. Downstream of the swirler, fluid rotation is most intense, and this decays as the flow moves through the tube. The rotating fluid is balanced by an inward pressure gradient. Hence, the pressure increases as the tube wall is approached, and the tube centreline pressure is a minimum immediately downstream of the swirler. Depending on the intensity of swirl, reversed flows along the centreline would appear as a result of the streamwise pressure increase along the centreline. When an air jet with $\dot{M}_j/\dot{M}=0.068$ is introduced concentrically into the swirling flow, the reversed flow regions are destroyed completely, and a positive U_o is observed for all measured x. A higher-momentum air jet will simply increase U_o along the centreline and give essentially the same behaviour. This is a consequence of the added axial momentum along the tube centreline, which increases the total pressure of the flow immediately downstream of the swirler. On the other hand, even a carbon dioxide jet with $\dot{M}_j/\dot{M}=0.472$ is not able to destroy the second reversed flow region completely. Instead, it simply pushes the start of the second reversed flow region axially downstream to about $x/D_j=33$. This is a consequence of the rapid decay of the jet because the heavier carbon dioxide elements are being thrown towards the tube wall by the swirl-induced centrifugal forces. When $\dot{M}_j/\dot{M}$ is decreased to 0.104, the second reversed flow region is observed to begin at $x/D_j\approx 20$. The almost five-fold increase in $\dot{M}_j/\dot{M}$ is only able to push the start of the reversed flow region further downstream by a distance of $x/D_j=13$. On the other hand, a relatively low momentum air jet ($\dot{M}_j/\dot{M}=0.068$) is able to eliminate the reversed flow regions completely. Therefore, this indicates that $\dot{M}_j/\dot{M}$ is not an important controlling parameter in this type of flow. The difference in behaviour is largely due to swirl and the density ratio ρ_j/ρ_a.

When $\rho_j/\rho_a=1$, a jet fluid element will be in equilibrium under the action of an outward centrifugal force and an inward pressure gradient. This equilibrium will be upset when $\rho_j/\rho_a\neq 1$. In the case of $\rho_j/\rho_a<1$, the jet fluid elements will be pushed back towards the centreline by the inward pressure gradients, which are greater than the centrifugal forces acting on the jet fluid elements at corresponding radial positions. As a result, the jet is preserved and the second reversed flow region is displaced radially outward[12] rather than axially downstream as observed in the case of carbon dioxide jets. When $\rho_j/\rho_a>1$, the jet fluid elements are carried away from the centreline because their centrifugal forces are greater than the inward pressure gradients at corresponding radial positions. Consequently, mixing between jet fluid and surrounding air is enhanced and this, in turn, will lead to a faster decay of the carbon dioxide jet compared with the air or helium/air jets. With more of the jet momentum dissipated by decay, less will be available to counter the second reversed flow region created by swirl. As a result, the reversed flow region is merely pushed axially downstream rather than destroyed.

A clear indication of the rapid decay of the carbon dioxide jets is shown in Fig 3 where the curves U_j/U_o versus x/D_j for the three different gas jets are plotted for comparison. They show clearly the rapid decay of the carbon dioxide jets and the much slower decay of the helium/air jet. In spite of the wide variation of $\dot{M}_j/\dot{M}$ for the air and carbon dioxide jets, the initial decay of the jets within the region $0<x/D_j<3$ is identical. Thereafter, centrifugal force dominates and gives rise to a very rapid decay of the carbon dioxide jets, independent of the $\dot{M}_j/\dot{M}$ ratio. As for helium/air jets, it is interesting to note that centrifugal force dominates immediately downstream of the jet nozzle. because of the large density difference between air and helium, and results in a slower decay for the helium/air jet, even in the region $0\leqslant x/D_j<3$. Further downstream, the centrifugal force effect becomes even more dominant, and the jet decay is practically reduced to zero. Once again, the results show that $\dot{M}_j/\dot{M}$ is not a controlling parameter in the high swirl number ($S=2.25$) flow.

The different behaviour of the three gas jets is summarized pictorially in Fig 4. It can be seen that if swirl is used to enhance

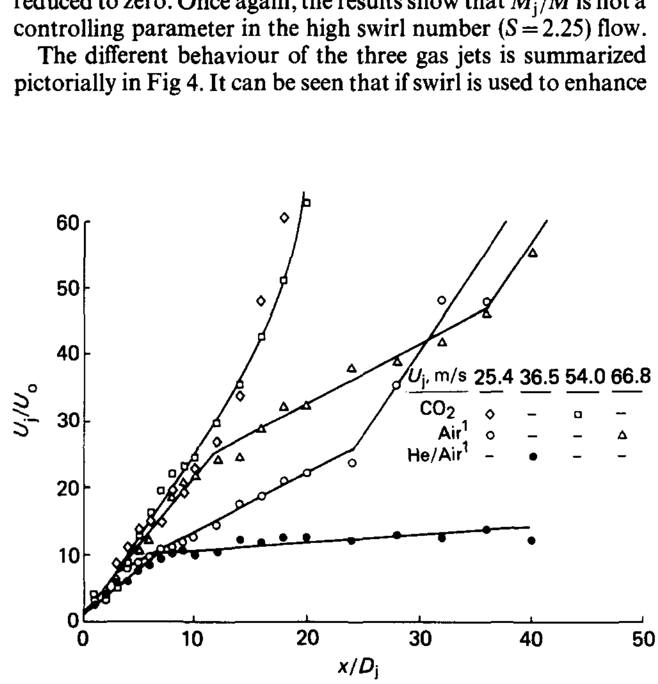

Figure 3 Behaviour of the inverse centreline mean axial velocity for jets in swirling flow

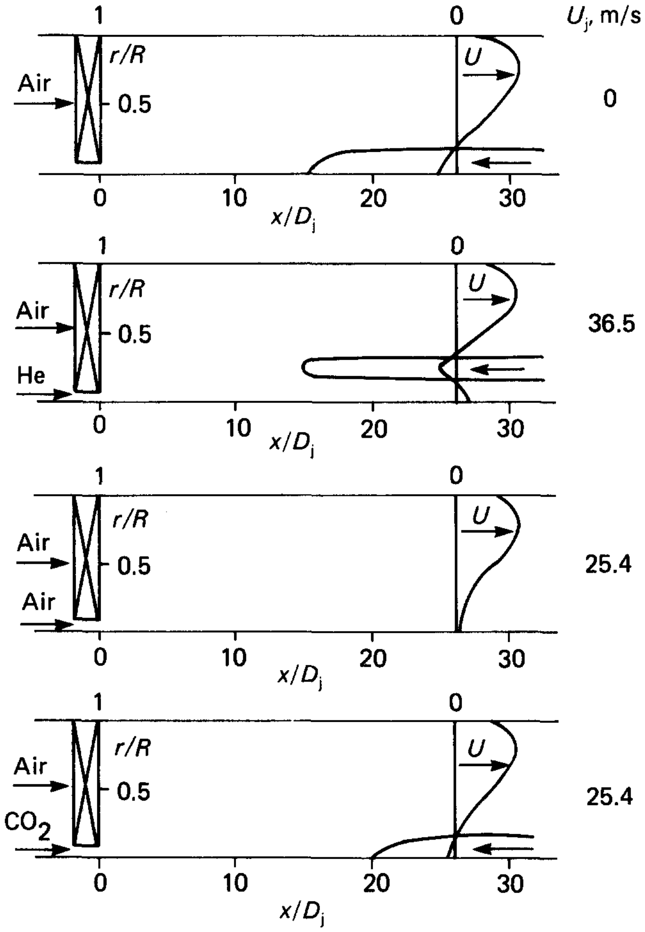

Figure 4 Pictorial representation of the flow in the combustor with different density gas jets

mixing in a combustor, it works best when the fuel and combustion product gas stream is heavier than the surrounding oxidant stream. On the other hand, if the oxidant stream is heavier, combustion efficiency would probably suffer because of the confinement of the fuel stream.

For homogeneous jet mixing, the centreline u'_0 and w'_0 values decay to those typical of the swirling flow only in a short distance of $x/D_j \approx 30$[11,12]. The rate of decay is independent of $\dot{M}_j/\dot{M}$, and the asymptotic value for u'_0 and w'_0 is about 1 m/s. At that point, the turbulence field is nearly isotropic. If higher density ratios (ie $\rho_j/\rho_a > 1$) contribute to enhanced mixing in the flow field, then one would expect u'_0 and w'_0 for carbon dioxide jets to be higher than their corresponding values for air jets. A comparison of the u'_0 and w'_0 behaviour for carbon dioxide and air jets is shown in Figs 5 and 6. The eventual values reached by u'_0 and w'_0 are 20–40% higher than those reached by homogeneous mixing, and do not seem to be as isotropic either.

So *et al*[14] have made a study of the behaviour of confined gas jets in the present facility. They found that the near fields of these confined jets are totally different from those of free jets, even though the confinement ratios is about 205. According to their findings, the presence of the jet is not felt immediately by the fluid at the tunnel exit. Consequently, the air column inside the test section is first compressed by the jet and then slowly pushed out of the tunnel. This behaviour causes the jet to spread radially rapidly and to decay quickly, resulting in the disappearance of the jet potential core even at $x/D_j = 1$. As a result, an equilibrium turbulence field, which bears striking similarity to that found in self-preserving, turbulent free jets, is established at $x/D_j \leq 2$. Finally, the behaviour is found to be completely independent of jet fluid densities and velocities. When the jets are issued into a confined body of swirling air with a solid-body rotation core instead of into a stationary air column, the jets are found to decay even faster[11]. The reason is that the rotating air column appears to be more rigid and therefore offers more resistance to the incoming jets. In the case of carbon dioxide jets, radial jet fluid displacement due to jet impingement on the confined fluid column is enhanced by the centrifugal force which tends to further displace the jet fluid elements outward away from the centreline. As a result, the jet decays faster and gives rise to a more intense turbulence field. When the jet momentum is increased, the radial displacement effect is more pronounced, and this, in turn, leads to a more intense mixing and ultimately higher levels of u'_0 and w'_0 (Figs 5 and 6). Therefore, from the combustor design point of view, it would be more beneficial for flame anchoring, complete combustion and thorough mixing to have the fuel and combustion product gas jet density higher than the surrounding swirling air.

Velocity field behaviour

The normalized mean and turbulent axial and circumferential velocities for carbon dioxide and air jets at different x/D_j

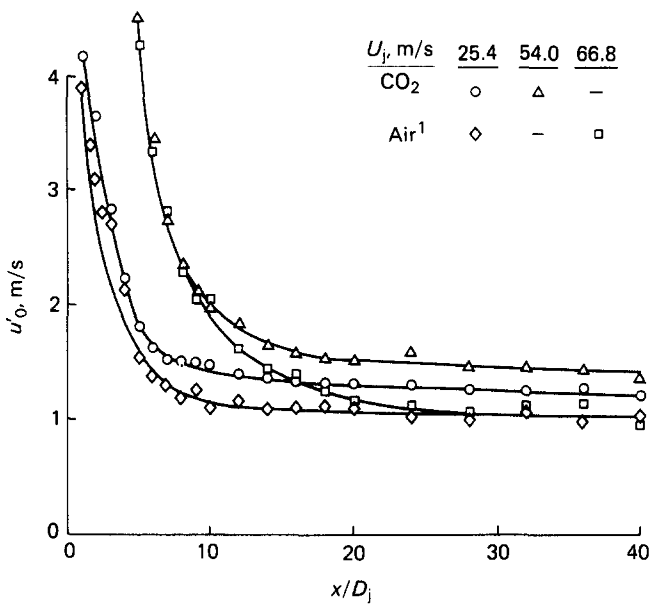

Figure 5 Decay of centreline rms axial fluctuating velocity

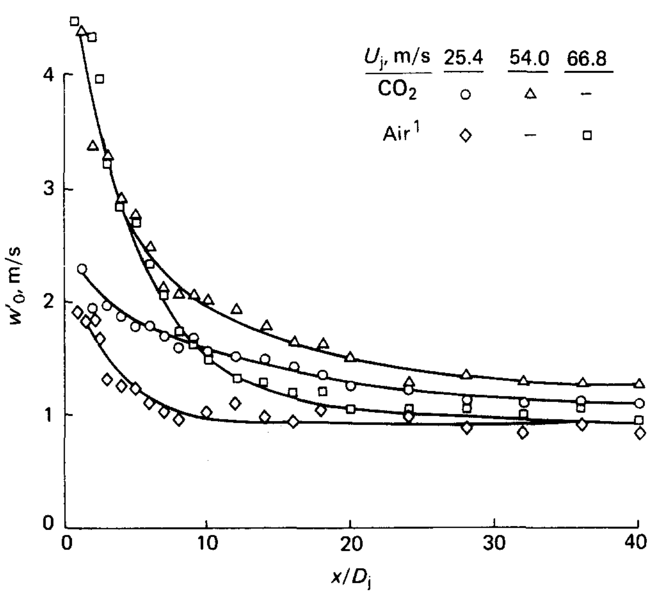

Figure 6 Decay of centreline rms circumferential fluctuating velocity

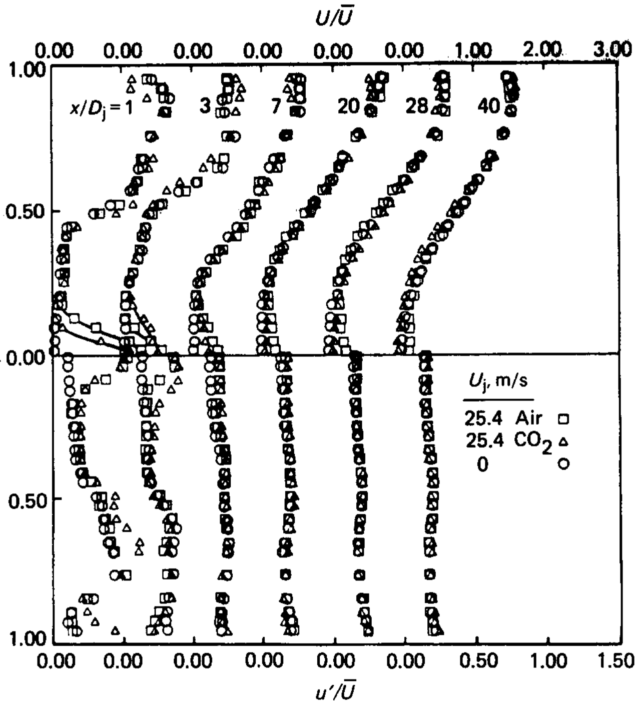

Figure 7 A comparison of axial velocity profiles for air and carbon dioxide jets with $U_j/=25.4$ m/s

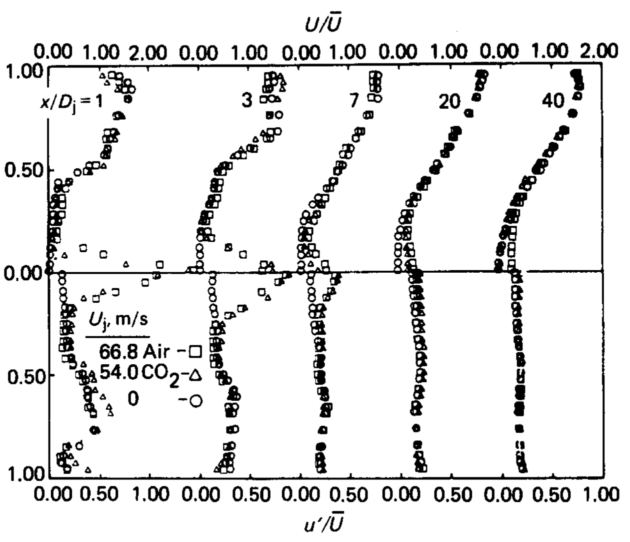

Figure 8 A comparison of axial velocity profiles for air and carbon dioxide jets with $\dot{M}_j/\dot{M}=0.47$

locations are shown for comparison in Figs 7–9. Included in the plots are also the case for $U_j=0$, which provide the velocity distributions for the swirling flow in the absence of a central jet. The results clearly indicate the rapid decay of the carbon jets compared with the air jets. The effect of the jet on the confined swirling flow is limited to a small region near the core only and has little or no influence on the flow outside the core (Figs 7 and 8). Also, the radial extent of the reversed flow region does not seem to be affected by the carbon dioxide jets either (Figs 4, 7 and 8). As for the circumferential velocity, the jet's effect is insignificant even at $x/D_j=1$ (Fig 9). This is true for both carbon dioxide and air jets. Since the jet only adds axial momentum to the flow, and jet splashing plus centrifugal force effects only contribute to the radial motion of the jet fluid elements, it is reasonable to observe that the jet has little effect on the distribution of $W(r)$.

The turbulence intensities $u'(r)$ and $w'(r)$ are again normalized by $\bar{U}$ for presentation. Comparison plots of $u'/\bar{U}$ and $w'/\bar{U}$ for carbon dioxide and air jets and for the case $U_j=0$ are shown in Figs 7–9. A plot to show the isotropic behaviour, or lack thereof, of the turbulence field for carbon dioxide jets is given in Fig 10. The entire turbulence field is affected by the introduction of a carbon dioxide jet. This disturbance is more pronounced in the near field, and it dies out rapidly as the jet moves downstream (Figs 7 and 8). For small $\dot{M}_j/\dot{M}$ (Fig 7), the effect of the jet on the turbulence field disappears altogether by the time the flow reaches $x/D_j \approx 10$. However, when $\dot{M}_j/\dot{M}$ is increased to about 0.47, the effect is still there even at $x/D_j=40$ (Fig 8). The same cannot be said for the air jets. In those cases, the effect of the jet is limited to a small region near the core. Again, this difference in behaviour can be effectively explained by the centrifugal force acting on the heavier jet fluid elements. As in the behaviour of the mean field, the jet, be it carbon dioxide or air, has little influence on the distributions of $w'(r)$, even though the eventual level of w' reached by the different jet is slightly different (Figs 6 and 9). Finally, the isotropic behaviour of the turbulence field with a carbon dioxide jet present in the confined flow is illustrated in Fig 10. Although the turbulence intensity levels reached by the flow for the two different U_j values are different, the near identical distributions of $\bar{u}'/U$ and $\bar{w}'/U$ for each U_j are quite evident. This means that the normalized turbulence field for carbon dioxide jets has again approached that for the swirling flow in the absence of a central jet.

Conclusions

An experiment on jet mixing in a confined swirling flow with jet fluid heavier than the surrounding swirling air was carried out. The results show that jet splashing and centrifugal force acting

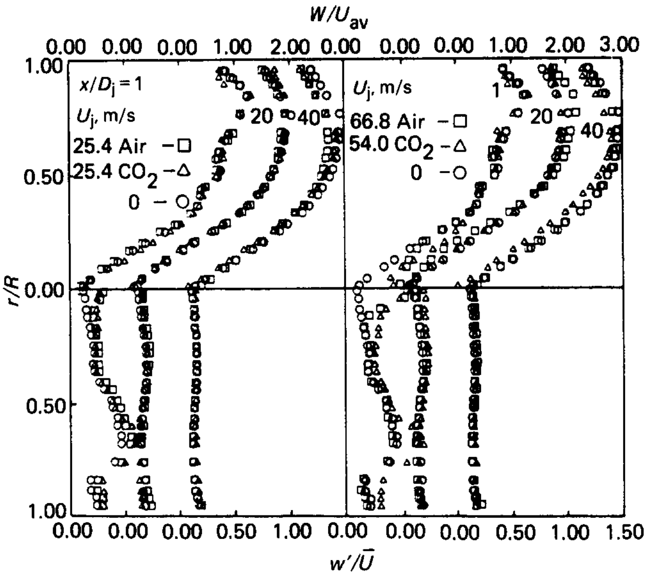

Figure 9 A comparison of circumferential velocity profiles for air and carbon dioxide jets

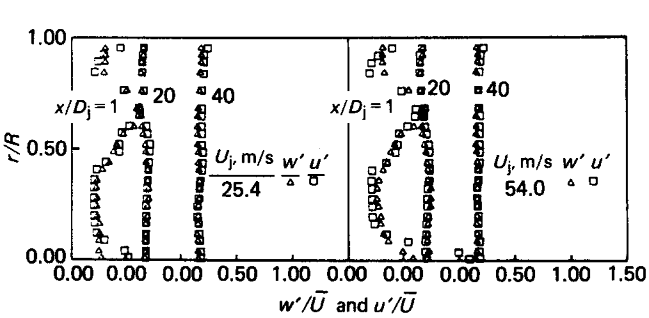

Figure 10 A comparison of u' and w' profiles for carbon dioxide jets at different x/D_j locations

on the jet fluid elements combined together to cause the jet to decay at a rate much faster than that observed in the homogeneous mixing case. Because of this rapid decay, the jet was not able to destroy the second reversed flow region as in the case of homogeneous jet mixing. If the jet fluid density was the same as the surrounding air, the jet effect on the flow field, independent of jet momentum, was limited to a small region near the core of the confinement. When the jet fluid density was higher, the effect of the jet was also felt away from the core because of the enhanced radial motion of the jet fluid elements. This influence was most pronounced in the near axial velocity field. Howeever, it quickly died out for lower momentum jets. Increasing the jet momentum increased the axial region of influence. For a carbon dioxide jet with momentum ratio $\dot{M}_j/\dot{M} \approx 0.47$, the influence could still be felt at $x/D_j = 40$. In view of these observations, it is reasonable to assume that combustor performance can be improved by designing a combustor with a fuel and product gas stream that is heavier than the surrounding oxidant air.

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