FLOW CHARACTERISTICS OF ISOTHERMAL SUDDENLY EXPANDING SWIRLING FLOW IN AN INDUSTRIAL BURNER WITH BLUFF BODY

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This paper describes an experimental study of flow characteristics of isothermal axisymmetric suddenly expanding swirling flow with bluff body using a backward-scatter two-component laser-Doppler velocimeter. Axial and tangential velocity components including time-mean and rms fluctuating values are determined. Some quantitative information, such as the boundary and strength of the reverse-flow zone, are provided.

Introduction

Swirling flows exiting from a circular duct or register into a chamber or duct of larger cross-section are widely used in combustion systems^{2-5,10)} and chemical reactors^{6,9)} because of their ability to provide intensive mixing in a small volume. The production of turbulence is increased above that of non-swirling flow by the presence of the tangential velocity component, which results in additional velocity gradients. Above a certain critical swirl intensity the mixing is further enhanced by the formation of an internal (central) reverse-flow zone. The recirculating fluid generates regions of high turbulence in the shear layer between the reverse flow and the surrounding forward flow, and serves to stabilize the flame by returning the hot combustion products to ignite the incoming combustible mixture.

The flow field generated by most swirl burners and combustors may be approximated as a swirling jet issuing into an expansion, in which reverse flow begins immediately downstream of the expansion. For the sudden expansion case, Hallett *et al.*^{7,8)} have studied experimentally the critical or minimum swirl level needed to produce recirculation as a function of expansion ratio and inlet conditions, and they also estimated the critical swirl number theoretically by a simple momentum integral model. The effect of swirl intensity on the flow and mixing of swirling air flow in a sudden expansion in a model of chemical reactor,

was also investigated.⁶⁾ Recently Usui *et al.*¹¹⁾ have studied the recirculating flow characteristics about the eddy near the wall in a confined space with axisymmetric sudden expansion followed by a conical contraction. However, the characteristics of swirling, expanding flows with a bluff body have not been well investigated. Initial studies performed at the IFRF⁵⁾ have shown that the bluff body can interact with the swirling flow field, increasing the reverse mass flow and mixing in the beginning of the internal recirculation zone. The aim of this paper is to provide the axial and tangential velocity profiles of time-mean values and root mean square fluctuations, the strength and boundary of the reverse flow zone, and the turbulent kinetic energies. The axial and tangential velocities were simultaneously measured here by a two-component, backward-scatter laser-Doppler velocimeter (LDV) system, which is nonintrusive, extremely reliable and widely used for isothermal^{2,5)} and combustion^{2,3,10)} swirling flow fields.

1. Experimental

1.1 Apparatus

The experimental combustor geometry with swirl is shown in Fig. 1. The air flow is introduced into the wind box, where the air passes through a successive series of honeycombs and mesh screens. Nonreacting swirling flows, with inlet swirl numbers S_0 of 1.95 and 1.05, are generated by axial-vane swirl generators. The definition of swirl number most commonly accepted is^{1,4,5,6)}

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Fig. 1. Geometry of experimental combustor with swirl

Fig. 2. Two-component laser-Doppler velocimeter and data acquisition

$$S = \frac{G_\phi}{G_x \cdot R} = \frac{2\pi \int_0^R \rho \bar{U} \bar{W} r dr}{2\pi R \cdot \int_0^R \rho \bar{U}^2 r dr} \quad (1)$$

where G_ϕ is the axial flux of angular momentum, G_x is the axial flux of axial momentum and R is the radius of swirl generator exit.

The swirling flow passes through the throat section of diameter $a=0.19$ m, and enters a cylindrical chamber of diameter $D_f=0.4$ m and length 4 m via a sudden expansion. The blockage ratio of the bluff

body, Db/a , equals 0.5. The quarl and furnace confinements are made from transparent plastic and have a measuring slot on their side wall. The air flow is contracted at the furnace exit via a gradual convergent quarl. The mean inlet flow velocity U_0 of the air flow is 8 m/s and the Reynolds number is 5×10^4 based on the throat section.

1.2 Velocity Measurements

Mean and root mean square (*rms*) velocity measurements, axial and tangential, were made simultaneously, using the two-component laser-Doppler velocimeter (LDV) system shown in Fig. 2. LDV

uses the optical Doppler effect to determine the fluid velocity, offering the advantage of calibration-free, nonintrusive measurements. The beam from a 4W Argon-ion laser (Coherent Innova model 70-4) was collimated and passed through a prism to separate the various wavelengths. The two most intense beams, green (514 nm) and blue (488 nm), were each polarized and split into two beams of equal intensity 40 mm apart. A 20 MHz frequency shift (by rotating diffraction grating) was applied to one beam of each beam pair to allow discrimination between the forward and reverse velocities, which is necessary for measurements in a reverse-flow zone. The four beams were then focused through a 1000-mm lens to a common point within the test section.

Receiving optics consisted of a 500-mm lens focused on a 1-mm-diameter photomultiplier tube aperture where the light signals are converted to electrical signals. These optics were placed by backward scattering. Signal validation was obtained using two counter processors (Aerometrics PDP-3200) directly with a computer system (Aerometrics DMS-400). The air flow was seeded with the smoke of paraffin oil having particle diameters mostly less than 1 μm . The particles were fed from the wind box and introduced to the air stream. This LDV system (Aerometrics LDV-200) has the capability to measure velocities over the velocity ranges $-80 < \bar{U} < 200$ m/s and $-80 < \bar{W} < 200$ m/s.

The LDV system was mounted on a traversing system which allowed movement of the measuring volume along any of three mutually orthogonal axes. The traversing system can be lowered to a minimum height of 58 mm.

To obtain statistically reliable mean and *rms* velocities, the number of data events has to be sufficiently large. Typically, 3000 data events were taken at each measurement point. When 10 units of 3000 data events were tested to obtain the "true" average value for one measuring point. It was found that the mean velocity deviated from the "true" mean value by $\pm 0.5\%$, and the *rms* velocity deviated from the "true" mean *rms* values by $\pm 4\%$.

2. Experimental Results and Discussion

2.1 Axial and Tangential Velocity Profiles

The inlet axial and tangential velocity profiles just downstream of the swirl generator ($x = -60$ mm) for $S_0 = 1.95$ are shown in Fig. 3. Similar profiles were obtained for $S_0 = 1.05$ (not shown). The tangential velocity profile is generally discussed in terms of forced vortex flow (solid body rotation) and free vortex flow (potential vortex).^{1,4,5} The forced vortex is characterized by the equation $\bar{W} = cr$ and is rotational (non-zero vorticity), while the free vortex is characterized by $\bar{W} = c'/r$ and is irrotational (zero vor-

Fig. 3. Radial profiles of normalized inlet mean velocities ($S_0 = 1.95$) ($x = -60$ mm)

ticity). It is found in Fig. 3 that the inlet tangential velocity profiles ($\bar{W}$) were a combination of forced and free vortex distributions, which is the so-called Rankine vortex. The inlet axial velocities ($\bar{U}$) were nearly uniform except within the small rotational core as seen in the tangential velocity profile. This velocity drop near the bluff body may be due to boundary layer effects.⁵⁾

The mean axial and tangential velocity profiles for $S_0 = 1.95$ and 1.05 are shown in Figs. 4 and 5, and the corresponding *rms* velocity profiles in Figs. 6 and 7, respectively. In these figures, the axial values appear in the top half and the tangential values in the bottom half. The velocity measurements showed the flow to be axisymmetric to a high accuracy so that the whole domain can be described by a radial profile. The measuring error was estimated by comparing metered mass flows with those integrated from the mean axial velocity profiles assuming axisymmetric flow. The latter was found to be within $\pm 10\%$, except for cases having regions of strong reverse flow and high turbulence level, up to 36% near $x = 250$ mm. This is relatively acceptable for velocity measurements of swirling flows.^{2,3,5,7,10)}

As shown in Figs. 4 and 5, it was found that the tangential velocity profiles remained a Rankine vortex type as the flow entered the throat section, and were well-developed after $x = 310$ mm, where values were $\bar{W}/U_0 = 1.0$ ($S_0 = 1.95$) and $\bar{W}/U_0 = 0.55$ ($S_0 = 1.05$) for $r/D_f > 0.1$. The larger the inlet swirl number, the larger the radius of rotational core in the throat section. Furthermore it was noted that the combustor geometry was axisymmetric since these on-axis ($r = 0$) tangential velocities approached zero.

For $S_0 = 1.95$, reverse-flow zones were present between $r/D_f = 0-0.1$ as the flow entered the throat

Fig. 4. Radial profiles of normalized mean velocities ($S_0 = 1.95$)

Fig. 5. Radial profiles of normalized mean velocities ($S_0 = 1.05$)

Fig. 6. Radial profiles of normalized *rms* fluctuating velocities ($S_0 = 1.95$).

Fig. 7. Radial profiles of normalized *rms* fluctuating velocities ($S_0 = 1.05$).

section, and off-axis between about $r/D_f = 0.1$ – 0.25 after sudden expansion. Even at $x = 920$ mm, a reverse-flow region still existed. For $S_0 = 1.05$, the reverse-flow zone was relatively smaller in the throat section, and on-axis between $r/D_f = 0$ – 0.1 in the furnace before $x = 390$ mm. The peak reverse flow velocities were about $0.78U_0$ ($x = 70$ mm) for $S_0 = 1.95$ and $0.33U_0$ ($x = 200$ mm) for $S_0 = 1.05$. It was noted that in both cases the slight increase in centerline mean axial velocities was due to the effect of furnace exit contraction. Just downstream of the sudden expansion, small external recirculation flow regions were found in both cases.

In Figs 6 and 7 it is seen that the W_{rms} velocities for $S_0 = 1.95$ were always larger than those for the $S_0 = 1.05$ case in the throat section. In both cases, W_{rms} was not less than U_{rms} along the centerline. In most of the region except near the centerline, the turbulent fields achieved similar values of U_{rms} and W_{rms} and flat *rms* velocity profiles were revealed. This swirl-flow field seemed to be responsible for the nearly isotropic velocity fluctuations.^{2,5)}

2.2 Strength and Boundary of Reverse Flow

In this work, the reverse-flow zone did not include the external recirculation zone. The reverse mass-flow rate, Mr , in the axial direction at any section of the reverse-flow zone is given by^{1,5)}

$$Mr = 2\pi\rho \int_{r_{u1}}^{r_{u2}} \bar{U}_n r dr \quad (2)$$

where r_{u1} and r_{u2} are the radial positions of zero mean axial velocity and $\bar{U}_n$ is the negative mean axial velocity. If a central reverse-flow zone existed at a given section, $r_{u1} = 0$. The axial distributions of the normalized reverse mass-flow rate, Mr/Mo , are shown in Fig. 8, where Mo is the inlet mass-flow rate. It was found that the maximum reverse mass-flow rate (defined as the strength of reverse flow) was

Fig. 8. Axial distributions of reverse mass-flow rate; ↓ indicates the axial position of throat section exit

$Mr/Mo = 13.1\%$ at $x/D_f = 0.63$ for $S_0 = 1.05$. The reverse mass-flow rate inside the throat section was about 2% of the total reverse mass-flow rate, as seen in Fig. 5, and Mr/Mo approached zero near $x/D_f = 1.5$.

As shown in Fig. 8 the reverse flow develops strength rapidly upon entering the sudden expansion. As observed in other investigations,⁵⁾ the major effect of the bluff body is to shift the location of the maximum strength of the internal recirculation zone upstream into the quarl. The rapid development of the reverse flow can be important in burner design, providing more rapid ignition and mixing.

For $S_0 = 1.95$, the recirculation zone extended into the throat section. The reverse mass flow rate of the first recirculation zone (Fig. 8) was less than 10% of the total reverse mass flow rate. After the flow exits the quarl into the furnace section the reverse mass flow increases rapidly. The second stronger zone of recirculation has forward flow on the furnace axis surrounded by reverse flow. The probable cause for the forward flow on the furnace axis is the contraction

Fig. 9. Reverse flow boundary and zero streamline profiles ($S_0 = 1.95$)

Fig. 10. Reverse flow boundary and zero streamline profiles ($S_0 = 1.05$)

at the furnace exit. The swirling flow in the furnace is highly subcritical,⁵⁾ implying that the fluid will be affected by the downstream furnace geometry.

Stream functions were obtained by integrating mean axial velocity profiles, using the equation^{1,5)}

$$\Psi|_r = 2\pi\rho \int_0^r \bar{U}rdr \quad (3)$$

The stream function may equal zero at more than one radial position, i.e. $r = r_{s1}$, $r = r_{s2}$, etc. The reverse-flow boundary and zero streamline profiles were shown in Figs. 9–10 for $S_0 = 1.95$ and $S_0 = 1.05$, respectively.

It was found that the widest parts of the reverse-flow zone were at $x/D_f = 0.9$ ($S_0 = 1.95$) and $x/D_f = 0.78$ ($S_0 = 1.05$). These positions were located just downstream of the position of maximum reverse mass-flow rate ($x/D_f = 0.78$ and 0.63 , respectively), as reported in the literature.⁵⁾ It was noted that for $S_0 = 1.95$ no closure of the reverse-flow zone could be found. Instead, a columnar reverse core flow followed the reverse-flow zone as indicated in Fig. 4 at $x = 920$ mm.

Conclusion

A backward-scatter two-component laser-Doppler velocimeter has proved its usefulness in determining

the flow behavior of an isothermal suddenly expanding swirling flow. Measurements of mean axial and tangential velocities and the corresponding velocity fluctuations have improved the understanding of the reverse flow characteristics. The widest parts of the reverse flow zone were located just downstream of the position of the maximum reverse mass-flow rate. At higher inlet swirl numbers no closure of the reverse flow zone was found. Instead, it was followed by a columnar reverse core flow.

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Nomenclature

a	= diameter of the throat section	[m]
c, c'	= constants	[—]
D_b	= diameter of the bluff body	[m]
D_f	= diameter of the furnace section	[m]
G_x	= axial flux of the axial momentum	[N]
G_ϕ	= axial flux of the angular momentum	[N.m]
Mr	= reverse mass-flow rate	[Kg/s]
Mo	= inlet mass-flow rate	[Kg/s]
R	= radius of the swirl generator exist	[m]
r	= radial coordinate	[m]
S_0	= inlet swirl number	[—]
U_0	= inlet mean axial velocity	[m/s]
$\bar{U}_n$	= negative mean axial velocity	[m/s]
$\bar{U}, \bar{W}$	= mean axial and tangential velocities, respectively	[m/s]
$Urms, Wrms$	= rms axial and tangential fluctuating velocities, respectively	[m/s]
x	= axial coordinate	[m]
Ψ	= stream function	[Kg/s]
ρ	= density of the air flow	[Kg/m ³]

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