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Blowout Behavior and Attachment Mechanism of Coaxial-Flow Jet Diffusion Flames*

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The blowoff and blowout behaviors and the mechanism of attachment to the burner port were examined experimentally for coaxial-flow jet diffusion flames, paying attention to the effects of the rim thickness, velocity combination and swirl intensity. A recirculating flow is formed in the wake of the burner rim, which plays a major role in the process of flame attachment especially for thick-rim burners. The blowout and blowoff limits, therefore, are expressed in a universal form in terms of the momentum flux ratio of the fuel jet to the coaxial air stream and of the velocity of the latter, since the momentum flux ratio governs the configuration of the recirculation zone whereas the latter is related to the intensity of shear or turbulence in and around the recirculation zone.

1. Introduction

A coaxial-flow jet diffusion flame is the prototype of most industrial flames, so that its attachment to the burner port is of practical significance for stable combustion. Although the blowoff behavior of open jet diffusion flames has been investigated by Hattori⁽¹⁾, Vanquickenborne and van Tiggelen⁽²⁾ and many other investigators, there is only Saima's investigation⁽³⁾ as for nonlifted flames stabilized above a thick-rim burner, and no information is found pertaining to those stabilized in a coaxial air stream.

In the present investigation, the blowout and blowoff limits of coaxial-flow jet diffusion flames were determined for various combinations of the velocity, intensity of swirl of the coaxial air stream, the fuel type and the thickness of the burner rim. In addition, observation was carried out of the state of flame attachment to the burner port and of the configuration of the recirculation zone formed in the wake of the burner rim. The distributions of temperatures and species concentrations were determined in and around the recirculation zone, the contribution of which to the state of flame attachment was examined.

As a result, the blowoff and blowout behaviors of coaxial-flow jet diffusion flames were successfully expressed in terms of the momentum flux ratio of the central fuel jet to the coaxial air stream and the velocity of the latter.

2. Description of experiment

The coaxial-flow jet diffusion flame

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burner used in the experiment is illustrated in Fig.1. The burner is of vertical type and has a Pyrex combustion tube of 50 mm i.d. and 300 mm or 380 mm long. The burner tube is of 7.6 mm i.d., and its rim thickness can be varied in steps of 0.5, 1, 2, 3, 4 and 6 mm by exchanging the port piece.

An air preheater is installed in the bottom of the burner system, which is not used in the present experiment. The intensity of swirl is adjusted by the ratio of feed rate of the tangential air to the axial air. A convergent nozzle, the area ratio of which is 1 to 4, is provided at the bottom entrance of the combustion tube to obtain a uniform air stream.

A hydrogen feed line was connected to

Fig.1 Burner system

the fuel feed line for the operational convenience in the determination procedure of blowoff or blowout limit. A feeder of magnesium oxide powder was inserted into the fuel feed line for the purpose of flow visualization, when the recirculating flow in the wake of the burner rim was observed. The stream was illuminated by a plane light beam of 1 mm thick including the burner axis to be photographed.

The local temperature in and around the recirculation zone was measured with a Pt-30 %Rh/Pt-6%Rh thermocouple of 0.1 mm wire diameter coated with silicon oxide. Since the fluctuation in temperature was considerably violent, the output signal of the thermocouple was averaged over 15 seconds using an integrator. The correction for conduction and radiation losses was omitted.

The local concentrations of chemical species, H_2 , O_2 , N_2 , CO , CO_2 and hydrocarbons lower than C_4 , were determined by analyzing the gas sample taken with a quartz microprobe by gas chromatography. The nozzle and outer diameters of the microprobe are ca. 0.1 mm and 4 mm, respectively, and the sampling rate is ca. 0.2 l/min.

The fuel used is propane. Observation of blowout behavior was carried out also for methane-air flames.

3. Velocity distribution in approach air stream

The velocity distribution in the coaxial air stream has been determined in the cross section at 1 mm above the burner port using a hot-wire anemometer. The velocity distribution in the boundary layer existing outside the burner tube is shown in Fig.2, where r is the radial distance and r_B is the outer diameter of the burner tube. The velocity gradient, g_C , in the boundary layer increases at a rate greater than that of the average flow velocity, u_C . This velocity distribution is affected only slightly by the rim thickness.

Then, the distributions of the axial

Fig.2 Velocity distributions in the boundary layer of nonswirling coaxial air stream

Fig.3 Velocity distributions in coaxial air stream with swirl

and tangential components, u and w , of velocity in the coaxial air stream have been determined in the same cross section using two hot-wire anemometers and an X-probe, the results being shown in Fig.3. It is noticed that the pattern of w -distribution is close to that of solid rotation except in the region close to the combustion tube wall, and that w is small near the burner tube.

4. Configuration of recirculation zone

The recirculating flow has been observed by the flow visualization technique for isothermal flows. It has been found that a closed recirculation zone consisting of two recirculating eddies, one on the fuel jet side and the other on the air stream side, develops above the burner rim, which is illustrated schematically in Fig.4.

The height, h_R , of the recirculation zone and the width, l_A , of the eddy on the fuel jet side are plotted against the momentum flux ratio, $(\rho_A u_A^2)/(\rho_C u_C^2)$, in Figs.5 and 6, where the rim thickness, t , is 4 mm for the former and 6 mm for the latter. The following empirical relations are obtained from these figures.

Fig.4 Recirculating flow (schematic)

Fig.5 Height of recirculation zone

$$h_R/t = 4.4 (\rho_A u_A^2 / \rho_C u_C^2) - 0.35 \quad (1)$$

for $t = 4 \text{ mm}$

$$z_A/t = (1 + 0.57 \rho_A u_A^2 / \rho_C u_C^2) - 1 \quad (2)$$

for $t = 6 \text{ mm}$

5. Observation of flame base

The direct photographs of the base of a propane-air flame are shown in Fig.7, where the rim thickness, t , is 3 mm and the velocity, u_C , of the coaxial air stream is 5 m/s. When the velocity, u_A , of the fuel jet is 9.2 m/s, the flame base is attached to the port stably as shown in Fig.7(c). As u_A is decreased from this condition, the flame base becomes gradually unstable, and fluctuates as shown in Fig.7(b). If u_A is decreased further, the flame base is partially lifted up as shown in Fig.7(a), finally being blown off entirely.

The u_A -value when the flame base is partially lifted up is called "lower blowout limit." If, conversely, u_A is increased from the state of Fig.7(c), the flame becomes extremely dark at about 10 mm above the port, finally beginning to oscillate violently with its base maintained stably in the recirculation zone as shown in Fig.7(d). This u_A -value is called "upper blowout limit."

A flame as shown in Fig.7(d) is observed only in a high-speed stream, the u_C -value of which is greater than 5 m/s. In a low-speed stream, the entire flame is suddenly blown out before oscillation starts. The oscillation of flame may result from a strong shear or turbulence at the junction of the fuel jet with the coaxial air stream above the recirculation zone which prevents the flame from spreading steadily out of the recirculation zone. In a low-speed stream, the recirculation zone diminishes as u_A increases so that no flame can be maintained in this zone.

Fig.6 Width of eddy on the fuel jet side

Figure 8 shows the location of the flame base in the recirculation zone for various u_A -values. This is a propane-air flame for $t = 3 \text{ mm}$ and $u_C = 1 \text{ m/s}$. The flame base moves inwards as u_A is increased from 0.6 m/s to 11.5 m/s.

For a thin-rim burner, the state of flame attachment is completely different from that of a thick-rim burner as shown in Fig.9. In this case, the flame base is located in the coaxial air stream outside the recirculation zone, and no flame exists in that zone. This suggests that the role of the recirculation zone has changed from one of an igniter to one of a stream decelerator so that the flame base stabilizes

(a) $u_A = 3.8 \text{ m/s}$ (b) $u_A = 6.4 \text{ m/s}$ (c) $u_A = 9.2 \text{ m/s}$ (d) $u_A = 11.5 \text{ m/s}$
Propane-air flames, $t = 3 \text{ mm}$, $u_C = 5 \text{ m/s}$.

Fig.7 Photographs of flame base

(a) $u_A = 0.6 \text{ m/s}$ (b) $u_A = 3.1 \text{ m/s}$ (c) $u_A = 8.7 \text{ m/s}$ (d) $u_A = 11.5 \text{ m/s}$
Propane-air flames, $t = 3 \text{ mm}$, $u_C = 1 \text{ m/s}$.

Fig.8 Location of flame base

Fig.9 Flame stabilized on a thin-rim burner

itself by the propagation mechanism.

For a thin-rim burner, the flame base moves outwards as u_A is raised with u_C kept constant. Then, the flame base begins to lift up at a u_A -value. The lifted portion is enlarged as u_A is raised further, and finally the entire flame is blown off. This u_A -value is called "flame blowoff limit" for a thin-rim burner.

Fig.10 Distributions of temperatures and species concentrations—Effects of velocity

6. Distributions of temperatures and species concentrations in and around the recirculation zone

The distributions of temperatures and species concentrations in the cross section at 4 mm above the port ($x = 4 \text{ mm}$) have been determined. The velocity, u_A , of fuel jet was varied in steps of 2, 4 and 8 m/s with the velocity, u_C , of coaxial air stream kept at 3 m/s. The results are shown in Fig.10, where ϕ and T denote the equivalence ratio and temperature, respectively, [HC] the sum of the mole fractions of individual hydrocarbons, [CO] the mole fraction of carbon monoxide, etc.

Hydrocarbons and oxygen coexist throughout the rim thickness, and the concentration

peaks of the products and reaction intermediates are rather flat, which implies the existence of violent recirculation or mixing. However, the locations of the concentration peaks of CO_2 and H_2O almost coincide with that of temperature peak. This suggests the existence of a flame or reaction surface even in the recirculation zone. The concentration peak of CO is also located close to the temperature peak, whereas that of H_2 which reacts more rapidly is shifted toward the fuel jet because of its rapid consumption. All the distribution curves including that of temperature shift toward the fuel jet as u_A is increased from 2 m/s to 8 m/s, which is in agreement with the movement of flame base illustrated in Fig.8.

The distributions of temperatures and species concentrations in the cross sections

at 2, 6 and 12 mm above the port are shown in Fig.11 for $u_A = 6$ m/s and $u_C = 3$ m/s. It is noticed that the peaks of the concentration curves of various species are gradually sharpened as they move upwards from the port. This implies that the thickness of the recirculation zone diminishes with distance from the port. Especially, it is highly probable that the cross section at 12 mm above the port is located above the recirculation zone.

The distribution maps of equivalence ratio, ϕ , and temperature, T , are shown in Figs.12 and 13, respectively. The flammable region where $\phi = 0.5 \sim 2$ shifts toward the fuel jet as u_A is raised, and the temperature peak moves following this movement. Comparing Fig.13 with Fig.8, the locus of temperature peak coincides well with the contour of flame base. Although a visible flame surface exists in the recirculation zone, chemical reaction appears to take place in almost the entire region of this zone, since most of the region, in which $\phi = 0.5 \sim 10$, is kept above 800 K and the concentrations of reaction intermediates, CO and H_2 , are at a high level.

7. Blowout and blowoff limits of flame

If the flame base is stabilized in the recirculation zone, the blowout behavior of a flame should be related to the velocity of coaxial air stream and the ratio of momentum flux of the fuel jet to that of the coaxial air stream, since the size and structure of the zone are governed by these quantities. Besides, the intensity of shear or turbulence in the recirculation zone and at the junction of the fuel jet

with the coaxial air stream above the zone is governed by u_C . Too intense shear or turbulence prevents a flame from maintaining itself in the recirculation zone or from spreading out of the zone. On the basis of this consideration, the blowout and blowoff limits of nonswirling flame are plotted on the $u_C - (\rho_A u_A^2) / (\rho_C u_C^2)$ plane in Fig.14 for propane-air and methane-air flames.

A flame is stabilized in the region between the upper and lower blowout limit curves for thick-rim burners. The upper blowout limits for both flames coincide with each other. When the rim thickness, t , is decreased below 2 mm for propane-air flames or 3 mm for methane-air flames, the state of flame attachment becomes of thin-rim burner type and the stability of flame becomes extremely poor. In this case, the flame is

(a) $x = 2$ mm

(b) $x = 6$ mm

(c) $x = 12$ mm

Fig.11 Distributions of temperatures and species concentrations at various heights

stabilized on the right of the blowoff limit curve. Since the velocity deficiency in the wake of the burner rim depends on the rim thickness, the blowoff limit is a function of the latter.

In Fig.14, the upper and lower blowout limit curves approach asymptotically the blowoff limit curves as u_C decreases. This is probably because the recirculation zone diminishes with u_C so that the flame base stabilizes itself by the propagation mechanism. In addition, the gradient of the upper blowout limit curve becomes steeper abruptly around $u_C = 6$ m/s. This is because flame starts to oscillate violently even if the flame base remains stably in the recirculation zone.

The effect of swirl of the coaxial air stream on the blowout and blowoff limits is

shown in Fig.15. When the swirl number, S_C , of the coaxial air stream is 0.5, the upper blowout limit is slightly lower and the lower blowout limit is slightly higher so that the stable flame region is slightly narrower as compared with the case that $S_C = 0$. The difference is, however, small, and S_C has no noticeable effect on the flame blowoff limit. Such slight effects of swirl of the coaxial air stream may be ascribed to the fact that the swirl is close to a solid rotation as shown in Fig.3 so that the tangential component, w , of velocity is small enough near the rim.

It is known, however, that swirl accelerates the mixing process. Therefore, it is

probable that the swirl of the coaxial air stream improves the combustion process and reduces the emissions of pollutants without much spoiling the stability of flame.

8. Discussion on the mechanism of flame attachment

On the basis of the above observation, the configuration of the recirculation zone and the state of flame attachment are illustrated schematically in Fig.16. Figure 16(a) corresponds to the case that u_C is so low that a recirculating flow does not develop enough. The flame base stabilizes itself above the recirculation zone by the propaga-

Fig.12 Distribution maps of equivalence ratio

Fig.13 Distribution maps of temperature

Fig. 14 Blowoff and blowout limits for nonswirling flames

Fig. 15 Effects of swirl in air stream on blowoff and blowout limits

Fig. 16 Illustrations of various states of flame attachment

tion mechanism.

Figure 16(b) represents a state close to the upper blowout limit, where the flame base is located close to the fuel jet. Since the relative widths of two recirculating eddies are determined by the location of the junction of the fuel jet with the coaxial air stream, the eddy neighboring to the fuel jet, which has a larger momentum flux, is smaller. The flame base is located within the eddy on the air stream side, since the stoichiometric fuel to air mass ratio is as small as about 0.06 for both methane and propane.

Figure 16(c) corresponds to a state close to the lower blowout limit, where the flame base is located close to the coaxial air stream. Since the flame base is located within the eddy on the air stream side, it is unstable and apt to lift up when the eddy is small and rapidly recirculating so that the intensity of shear in it is high.

Figure 16(d) represents the state in which u_A and u_c are so high that the intensity of shear or turbulence at the junction of the fuel jet with the air stream is too high for the flame to spread out of the recirculation zone.

Figure 16(e) shows the state of flame attachment for a thin-rim burner. Since the recirculation zone is so small that the intensity of shear and the heat loss within it are excessively high, the combustion reaction is not maintained in it and the flame base stabilizes itself in the coaxial air stream by the propagation mechanism.

9. Conclusions

The blowoff and blowout behaviors of coaxial-flow jet diffusion flames and the mechanism of attachment of flame base to the burner port have been examined with wide variation in velocities of fuel jet and coaxial air stream, in swirl intensity of the latter and in the rim thickness. The results are as follows.

(1) A closed recirculation zone consisting of two annular eddies, one on the fuel jet side and the other on the air stream side, is formed above the burner rim. The height of the recirculation zone and the relative widths of the annular eddies are

functions of the ratio of momentum flux of the fuel jet to the coaxial air stream.

(2) Although combustion reaction takes place almost all over the recirculation zone, a visible flame surface develops at the region where the equivalence ratio is between 1 and 2.

(3) For a thin-rim burner whose rim thickness is less than 1 ~ 2 mm for propane-air flames or less than

2 ~ 3 mm for methane-air flames, the flame base attaches to the burner port by the propagation mechanism, and is apt to blow off even at a low flow velocity.

(4) For a thick-rim burner, the upper and lower blowout limits exist and the stable flame region between them is wide. In a low-speed coaxial air stream, the velocity of which is less than 1 ~ 2 m/s, however, the mechanism of flame attachment resembles that of thin-rim burner, since the development of the recirculating flow is not sufficient.

(5) The blowout behavior of flames for a thick-rim burner is represented well by the ratio of momentum flux of the fuel jet to the coaxial air stream and the velocity of the latter.

(6) The swirl of the coaxial air stream has only slight effects on the flame blowoff and blowout limits.

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