ダブレット噴流による火炎の吹き消え制御に関する研究

陳仕敏サイモン*・高羽英樹**・矢野利明***・鳥居修一***

AN ANALYTICAL STUDY ON ENHANCEMENT OF FLAME BLOWOUT LIMITS BY DOUBLET FLOWS

Sze Man Simon CHAN, Hideki TAKABA, Toshiaki YANO and Shuichi TORI

Experiments have been carried out on turbulent jet diffusion flames stabilized on a fuel nozzle encompassed by an outer air-suction tube. Both the nozzle and tube were set in the form of a concentric annulus. Seven air-suction tubes were utilized for the study respectively. One of the tubes had the same height as the nozzle while the others had six different heights that formed six different height differentials against the nozzle. The effect of height differentials formed between the nozzle and the tubes on flame blowout limits enhancement was examined in details under non-doublet and doublet flows conditions. An intensive study on various lift-off flame morphologies was performed by employing real-time imaging video recording, image processing and Schlieren techniques in an attempt to unravel and elucidate the complicated morphologies from various dimensions. The effect was evaluated in terms of three parameters; namely flame lift-off height, fuel flow velocity and height differential formed between the outer tube and the nozzle. It has been found out that (i) the setting, namely that the outer tubes were higher than the nozzle, could generate a positive effect on enhancement of flame blowout limits under both non-doublet and doublet flows conditions (ii) this effect became more conspicuous and favorable when doublet flows were applied.

Key Words : Turbulent Diffusion Flames, Flame Stabilization, Blowout, Lift-off Flame, Doublet Flows

1. Introduction

Jet diffusion flames are widely utilized on industrial combustors, such as boilers and turbines, inasmuch as they can be easily controlled and safely handled during their combustion processes. In order to achieve higher combustion density, an intensified increase in fuel flow velocity is vital to secure an amplification of flame thermal stress. However, flame lift-off phenomenon occurs in the vicinity of fuel nozzle rim with an increase in fuel flow velocity to a certain extent. Several early studies of the transition from laminar to turbulent combustion in jet diffusion flames indicated that, as the velocity is increased from a low initial value, the flame increases in length. A further increase in fuel flow velocity will result in flame blowout.[1-4] Since jet diffusion flames are so widely used; flame stabilization, as well as, flame blowout limits enhancement is indispensable to the design of an appropriate combustor for sound and safety operation.

Numerous contemporary studies and experiments have been done on flame stabilization and enhancement of flame blowout limits. Jensen and Shipman utilized pilot flames to create flame stabilization effects.[5] Cambel employed gaseous jets to achieve flame stabilization.[6] Zukoski and Marble conducted a detailed research on the role of wake transition in the process of flame stabilization on bluff bodies.[7] Feikema and Chen utilized swirl to procure flame blowout limits enhancement effects.[8] Choudhury and Cambel reported their research on flame stabilization by wall recesses.[9] In addition to the above researches, studies on flame stabilization and enhancement of blowout limits by doublet flows have been carried out

---

平成11年5月31日受理

*博士前期課程機械工学専攻

**三五(株)

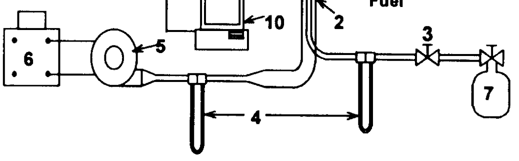
***機械工学科

by our research team. Doublet flows are formed using a concentric annulus, in which the circular free jet is injected from an inner fuel nozzle and the surrounding air is sucked into an outer tube encompassing the nozzle. A strong shear flow field is thereupon generated between the airflow and the opposite flow of fuel jet. It has been found that doublet flows could create a positive effect on dragging down the lift-off flame base towards the fuel nozzle. The unequivocal effect of doublet flows on its ability of flame blowout limits enhancement and flame stabilization has been also validated and reported in our previous research reports.[10-12]

The present study deals with an approach to unravel an unknown phenomenon emerged from the height differential h between the outer tube and fuel nozzle during non-doublet and doublet flows conditions. Effects on enhancement of flame blowout limits were evaluated in terms of three parameters; namely the flame lift-off height L_h, the fuel flow velocity U_f and the height differential h. A scrutinized study of the lift-off base fluctuation profile was performed to acquire a subtle analysis of the flame morphology. Several visualization techniques were also employed in an attempt to unravel and explicate the complicated phenomena occurred in the interim of both non-doublet and doublet flows utilization in addition to the effect subject to the height differentials.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the experimental apparatus is shown in Fig.1. The inner fuel nozzle had an inner diameter of 1.69mm and a rim thickness of 0.21mm. The fuel used in these experiments was propane. Amelioration was done on the original design of our initial experimental device, which created doublet flows.[10] Instead of establishing simply both the nozzle and outer tube in the form of a concentric annulus, six different height differentials between the nozzle and outer tube were induced. Seven outer tubes were employed for this study. One of them had the same height as the nozzle while the others had six different heights. The inner port diameter of the concentric air tubes was 22.3mm while its rim thickness was 1.35mm. Each of the tubes had their circular edges cut and sealed off by a transparent glass plate to facilitate visualization. The six height differentials h generated between the six tubes and the nozzle were 5mm, 10mm, 15mm, 20mm, 25mm and 30mm respectively. Three volumetric flow rates of air being sucked, Q_a, were predetermined which were $Q_a=0$, 1.0×10^{-3}m^3/s and 1.5×10^{-3}m^3/s respectively. Detail of experimental procedures as well as image processing and treatment, is the same as that of Ref 12. Several flow visualization techniques were used to reveal manifold features of the lift-off flame. These included real-time imaging video recording, image processing and schlieren techniques. Continuous time-wise of flame images were recorded by utilizing a video camera with its shutter speed set at 1/60. Time interval for each video shooting was 10 seconds. Recorded images were then replayed on a monitor linked with a time device (a video machine with time base correction function — Sony VIDEOPLUS EV-NS 9000NTSC) that enabled still-motion image revision. Meanwhile, the time device was also connected to a 32-bit personal computer installed with image treatment software (WINROOF). A binary threshold value of 110 was selected to enable an appropriate determination for the lift-off height, L_h. Schlieren pictures of the lift-off flame were also taken by using a high-speed video camera (nac HSV-500) with its shutter speed set at 1/500. Smoke gas from incense was employed to reveal the actual surrounding airflow due to the fact that burning incense was found to generate large quantities of particulate, which could be an expedient for visualization purpose.[13-14] Upon completion of these experiments, time-wise flame images data were translated into actual lift-off height values by means of WINROOF. Graphs for L_h against U_f at each of these



1. **Inner Fuel Nozzle**
2. **Outer Tube for Air Suction**
3. **Needle Valve**
4. **Orifice and Manometer**
5. **Blower**
6. **Voltage Alteration Device**
7. **Fuel Bomb**
8. **Video Camera**
9. **Time Device**
10. **Personal Computer (WINROOF)**

Fig.1 A schematic of experimental apparatus experiments were plotted to facilitate our analysis.

3. RESULTS AND DISCUSSION

3.1 Measurement of the height differential h against the fuel flow velocity U_f

The effect of height differentials on enhancement of flame blowout limits was verified by performing an analysis that juxtaposed experimental data of both the maximum fuel flow velocity U_b and the height differential h for comparison. U_b was procured after the flame had attained a position of stabilization at a certain height differential. The experimental results are summarized in Fig.2. As illustrated in this figure, U_b increases with h in all three Q_a setups. This observation was particularly conspicuous when doublet flows were applied. The maximum fuel flow velocity U_b increased to 48m/s when the height differential h became h ≥25mm and air-suction volumetric rate Q_a (1×10^{-3}m^3/s. This fuel flow velocity 48m/s is the maximum velocity that our research team could achieve among all of the similar experiments done so far. Another significant observation which is highlighted in the figure is that there is no flame blowout phenomenon when h ≥20mm and $Q_a \geq 1\times10^{-3}$m^3/s at which the maximum fuel flow velocity is U_b=48m/s. The lift-off behavior beyond U_b=48m/s was unknown as no fuel flow velocity higher than 48m/s could be attained. Nevertheless, experiments were carried out continuously when Q_a was set at 1.5×10^{-3}m^3/s with U_b stabilized at 48m/s. The fact that U_b increases with an increase in h validates a positive effect of height differentials on blowout limits enhancement. A further increase in U_b with an increase in both h and Q_a vindicates the double favorable effects induced by both doublet flows and height differentials.

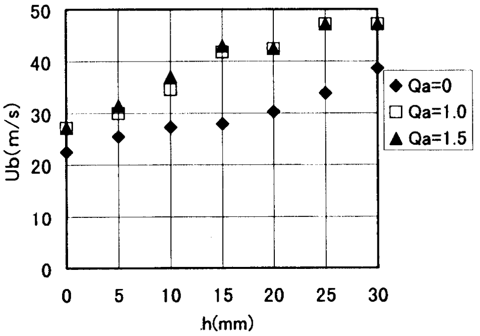


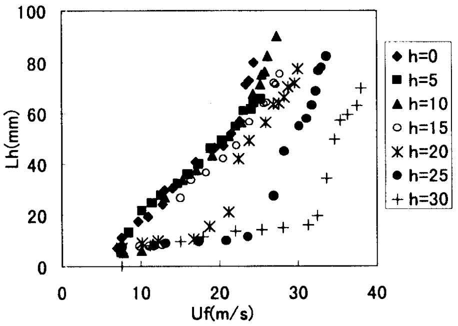
Fig.2 Measurement of the height differential h against the fuel flow velocity U_b

3.2 Measurement of the lift-off height Lh and the fuel flow velocity U_f

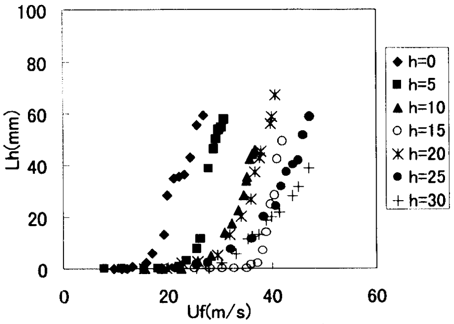
Fig.3 depicts an alternative way of translating experimental data into useful information for further analysis. The mean lift-off height L_h for each height differential and volumetric rate of air-suction setup was plotted against the fuel flow velocity U_f as shown in this figure. This figure comprises of two representative graphs juxtaposing together for comparison. It is obvious from the figure that L_h increases along with an increase in U_f. This result assents well to those of the earliest studies done by Hottel and Hawthorne.[1] Furthermore, this figure also reveals several distinct findings summarized as below:

1) The maximum fuel flow velocity U_b increases with the height differential h at Q_a=0. This correlation is perfectly consistent with that mentioned in section 3.1.

2) At each of the fuel flow velocities, mean lift-off heights decrease with an increase in height differentials. The rate of decrease becomes larger with an increase in Q_a. In addition to this observation, there are occasions of L_h=0 , only when doublet flows are applied. This observation further vin-



(a) Qa=0m^3/s



(b) Qa=1.5×10^{-3}m^3/s

Fig.3 Measurement of the lift-off height L_h against the fuel flow velocity U_f

dicates the favorable effect on enhancement of flame blowout limits by doublet flows and the positive height differentials.

It should be accentuated that L_h is a mean value that cannot reflect the actual flame lift-off phenomenon. No doubt $L_h=0$ can be seen in the figure, but it does not provide any factual evidence of the flame being stabilized at the nozzle rim without lift-off. The flame, in actuality, does lift off and reattach to the nozzle rim and the reattachment is remarkably frequent in the interim of doublet flows utilization.

3.3 Analysis of the lift-off phenomenon from schlieren images

Representative schlieren pictures were employed to elucidate divers flame lift-off morphologies subject to the following case studies:

(a) $h=0$, $Q_a=1\times10^{-3}\mathrm{m^3/s}$ and $U_f=23\mathrm{m/s}$

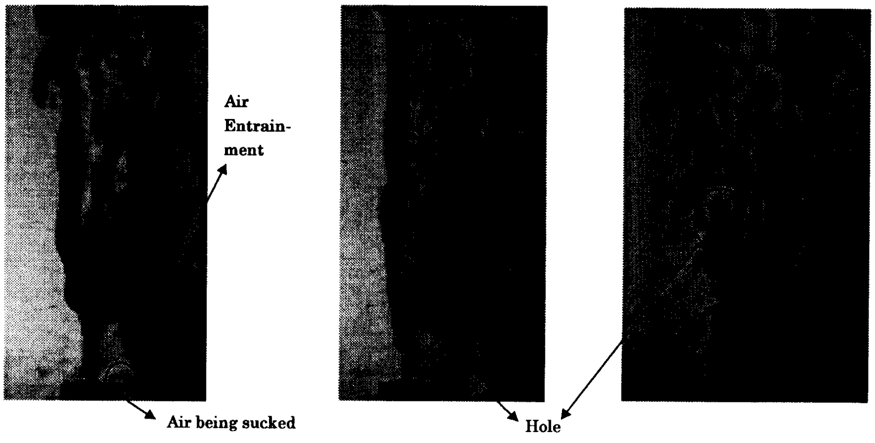
It can be seen from Fig.4 (a) that the mantle of hot gas visible in this picture is rather thick. The path of air being sucked into the outer tube is visible and is highlighted in this picture. It was observed during our experiments that only the surrounding air in the vicinity of the outer tube was sucked which indicates that the limited effective zone of doublet flows. Air entrainment is also noticeable. A helical motion, which developed in the shear layer bounding the gas jet and towards the top of the picture, could also be seen. This wave motion destabilized the gas jet as a whole and subsequently, the surrounding flame, which is consistent with the findings by Coats and Zhao.[14]

(b) $h=0$, $Q_a=1.5\times10^{-3}\mathrm{m^3/s}$ and $U_f=23\mathrm{m/s}$

As Q_a increased further, the lift-off behavior changed as depicted in Fig.4 (b). There was a pronounced necking of the outer mantle appeared in the hot gas region when the lift-off flame was being dragged down to the nozzle. Furthermore, hot gas at the outer mantle was seen to enter into the cold fuel gas region from time to time. Mixing effect of both the hot gas and cold fuel gas was observed to take place. Holes generated by air being sucked into the flame base were also found in the flame sheet. This observation would seem to correspond with the phenomenon described by Eickhoff et al.[16] The outer mantle, however, became thick again when the flame lifted off to the downstream.

(c) $h=30$, $Q_a=1.5\times10^{-3}\mathrm{m^3/s}$ and $U_f=45\mathrm{m/s}$

As Q_a increased further, holes emerged out rather frequently that the necking region at both sides of the flame appeared to be significantly narrow, as shown in Fig.4 (c). Vortices were visible at the flame base. The branch-like structures were torn asunder from time to time. Flame reattachment was seen to occur frequently. The vortical motion found in the interior region of the flame base might generate relatively high local strain rates and consequently, cause flame extinction in the necking region. This would seem to correspond with the phenomenon mentioned by Lewis et al that it might be able to explain why the necking region became narrower.[17] The breakdown of distinct shear layer between the hot gas and cold fuel gas into fickle mixing phenomena by the vortical motion effect could act as a damper to reduce the velocity of fuel gas that flew to the downstream. This vortical effect



(a) (b) (c)

Fig.4 Case studies of divers flame lift-off morphologies by means of sclieren technique might ascribe to the positive enhancement effect generated. Scholefield and Garside observed a hysteresis behavior in the flame lift-off and reattachment characteristics. The reattachment of a lifted flame required the reduction of gas velocity below its value at which the flame was lifted originally.[18] It is also known that flame blowouts occurs when burning velocity is no longer able to pursue the gas flow velocity. A decrease in gas velocity postulates an enhancement of flame blowout limits with a result of frequent reattachment. Further investigation and experiments have to be done to examine and fathom this phenomenon out, however.

4. Conclusions

The followings summarize the major conclusions of this present study:

1) The height differential alone could create a positive effect on enhancement of flame blowout limits. This effect was further strengthened with an increase in air-suction volumetric rate.

2) Mixing effect of both the hot and cold gas was found to grow progressively along with an increase in height differentials. It was not obvious in the case of h=0mm. It became conspicuous with vortices appeared in the flame base region. These vortices propagated further downstream when both the differential heights and volumetric rates of air-suction were increased. The mantle of the hot gas in the shear layer region became narrower (the necking region) as the mixing effect became more vigorous.

3) The mixing effect formed by both the height differentials and doublet flows could be considered as the prominent cause for the positive enhancement effect. Further investigation by means of Planar Laser-Induced Fluorescence (PLIF) technique as a judicious choice of methodology to measure OH concentrations and temperatures of the flame is, however, necessary to unravel the mysteries behind the veil of this prodigiously complicated phenomenon, though it seems to be a Gordian knot to accomplish.

Nomenclature

h	height differential between the outer tube and inner nozzle
L_h	flame lift-off height
Q_a	volumetric rate of air-suction

References

(1) Hottel and Hawthorne, 3rd Symp. (Int'l) on Combustion, 254 (1949)

(2) Scholefield et al, 3rd Symp. (Int'l) on Combustion, 102 (1949)

(3) Wohl et al, 3rd Symp. (Int'l) on Combustion, 288 (1949)

(4) Wohl, et al, 3rd Symp. (Int'l) on Combustion, 3 (1949)

(5) Jensen and Shipman, 7th Symp. (Int'l) on Combustion, 674- 680 (1959)

(6) Cambel, Combustion and Propulsion, 541-544 (1958)

(7) Zukoski and Marble, Combustion Researches and Reviews, 167-180 (1955)

(8) Feikema and Chen, Combustion and Flame, 80, 183-195 (1990)

(9) Choudhury and Cambel, 8th Symp. (Int'l) on Combustion, 963-970 (1962)

(10) Terashi et al, Proceedings of JSME, No. 968-3, 161-163 (1996)

(11) Iino et al, Proceedings of the 35th Japanese Symp. on Combustion, 7-9 (1997)

(12) Chan et al, Proceedings of the 36th Japanese Symp. on Combustion, 259-261 (1998)

(13) Mannix et al, "Physical characterization of incense aerosols", Sci. Total Environ, 193 (2), 149-158 (1996)

(14) Nagayama, "Visualization Techniques", p.69 Asakura Publishing Co., Ltd. (1998)

(15) Coats and Zhao, 22nd Symp. (Int'l) on Combustion, 685-692 (1988)

(16) Eickhoff et al, 20th Symp. (Int'l) on Combustion, 311 (1985)

(17) Lewis et al, 22nd Symp. (Int'l) on Combustion, 515-522 (1988)

(18) Scholefield and Garside, 3rd Symp. (Int'l) on Combustion, 102 (1949)