426 KSME International Journal, Vol. 14, No. 4, pp. 426~432, 2000

A New Flame-Stabilization Technology for Lean Mixtures

Duck-Jool Kim*
Professor, School of Mechanical Engineering, Pusan National University, Korea
Gyung-Min Choi
Researcher, Department of Mechanical Engineering, Osaka University, Japan

The development of a low-pollution burner is important for saving energy and preserving the environment. A low-pollution burner can be produced by lean-mixture combustion and general combustion technology. The flammable limit of premixed flame is narrower than that of diffusion flame. Producing a lean mixture of fuel results in an effective combustion condition, which in turn produces high load and low pollution. In this study, it was found that the influx of Q_2 had an effect on extending the lean flammable limits and flame stabilization in a doubled jet burner. And the flame, consisting of small eddies, can be stabilized by the nozzle neck phenomena.

Key Words : Low Pollution, Lean Flammable Limit, Flame Stabilization, Nozzle Neck Phenomena, Lean Mixture Combustion

Nomenclature

C : Correlation coefficient
CH : CH band luminescence intensity
I : Ion current
OH : OH band luminescence intensity
P* : Dynamic pressure which is divided by the maximum value at each cross-section (dimensionless)
Q_1 : Flow rate of the unburned mixture in the inclination direction (10^{-3} m^3/s)
Q_2 : Flow rate of unburned mixture in the central axis direction (10^{-3} m^3/s)
R : Radial axis (mm)
THC : Total hydrocarbon concentration
X : Central axis (mm)
τ : Time constant (mm)
Φ_o : Total applied equivalence ratio
Φ_1 : Applied equivalence ratio of the inclination direction mixture
Φ_2 : Applied equivalence ratio of the central axis direction mixture

* Corresponding Author,
E-mail : djkim@hyowon.pusan.ac.kr
TEL : +82-51-510-2316 ; **FAX** : +82-51-516-9598
Professor, School of Mechanical Engineering, Pusan National University, San 30, Jangjun-dong, Kumjung-ku, Pusan 609-735, Korea (Manuscript **Received** May 8, 1999; **Revised** October 13, 1999)

1. Introduction

A lean-mixture combustion is of great technical importance for the development of a low-pollution burner and for preserving the environment. A low-pollution burner may be produced by lean-mixture combustion and through general combustion technology. Heat is continuously generated from a flame. In general, premixed flame is more efficient in taking high load, than diffusion flame. However, the flammable limit of pre-mixed flame is narrower than that of diffusion flame. Therefore, lean, premixed flame is required for high-load, low-pollution combustion in order to broaden the narrow range of premixed flame.

Ballel and Lefebvre (1979) measured the lean flammable limits of flames by changing the dimension of the flame holder, pressure, temperature, velocity, and turbulent intensity of the supplied air. The experimental results were compared with numerically calculated ones, and then the influence of each factor on the flammable limits was estimated. Regenerative burners were developed by recovering the waste heat from the industrial-heated systems.

Masters, Webb, and Davies (1979) studied the use of modeling techniques in the design and application of a recuperative burner.

Dearden et al. (1996) investigated the NOx emission from high-temperature, air-preheated burners with air-staging.

Kotani and Takeno (1982) designed an entirely new burner to minimize heat loss. In their burner, a bundle of ceramic tubes was used as a combustion tube, and four perforated ceramic plates were placed upstream and downstream of the tube to reduce the radiative heat loss from a heated tube. The stability and combustion characteristics of a burner were studied to explore the range of flame stability which could be extended below the normal lean limit.

Takeno, Sato, and Hase (1981) attempted to predict the limits of flammability by considering the effects of the finite length of the porous solid inserted for internal heat recirculation.

Kawamura (1988) carried out an experimental study about the combustion of ultra-lean fuel and air mixture by heat recirculation.

However, these studies used lean combustion with heat exchangers or a heat recirculator. The systems used in the experiment were somewhat complex and expensive. The flame structure under lean combustion conditions was difficult to interpret in detail.

Therefore, we proposed a doubled jet burner that could extend the lean flammable limits by the characteristics of fluid dynamics. We studied the flame structure in detail under the conditions of lean mixture flame and the flame stabilization characteristics of a doubled jet burner.

2. Experimental System and Methods

2.1 Experimental system

Figure 1 shows a detailed diagram of a burner with a typical nozzle. LPG is used for fuel. The air-fuel mixture of flow rate Q_1, which collides with Q_2, is supplied with an 20 degree inclination. The air-fuel mixture of Q_2, which intensifies turbulence, is injected along the central axis. The diameter of the nozzle tip is 24mm.

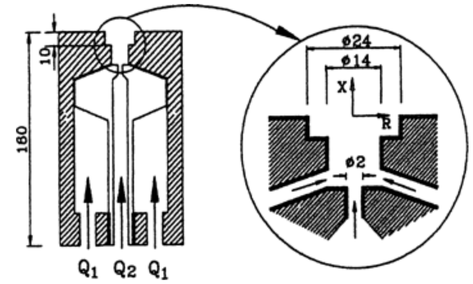


Fig. 1 Detailed diagram of a burner with a typical nozzle

Q_1 of mixture is injected through four tubes with same diameter. The flow field of inside burner is in fully developed turbulence, and then an impacting jet field is formed. To increase the shear force, a doubled impacting jet field is formed with Q_2. The coordinate system is shown in Fig. 1, and its origin is at the center of the nozzle tip.

2.2 Experimental methods and conditions

The flammable limit was determined by a supplied equivalence ratio when the flame blows out due to large oscillations near the nozzle tip. After forming a stable flame, the flow rate of Q_2 was increased until the flame extinction. The blowout of the flame was caused by large oscillations of large-scale eddies near the burner rim (Kido, Nakashima, Huang, and Kitano, 1990).

The turbulent characteristics around the rim of the unburned mixture were measured by a 5μm hot-wire anemometer. The dynamic pressures near the nozzle exit were measured using a pitot tube. We used the instantaneous micro-schlieren photography to elucidate the scale and distribution of eddies around the rim and the flow field.

The optical axis was fixed at X=15mm, and the diameter of the receiving lens was 26.8mm. The Averaged Distance between Successive Fringes (ADSF) is a qualitative eddy scale. To investigate the qualitative characteristics of the local eddies of flames, the local ion-current concentration was measured. Two ion probes parallel with the central axis were set to measure the local flame-front-propagating velocity. The distance between two ion probes varied from 2mm to 10mm. The local flame-front-propagating velocity was determined by measuring the distance between two probes and the delay time.

Chemiluminescence emitted by the exited intermediate species of flames immediately after their reaction can be an index of the overall reaction process. Dryer and Crosley (1985) studied fluorescence imaging for flame chemistry. For example, OH was one of the major intermediate species at high temperatures, CH was an indicator of the local heat release rate, and C_2 radicals were produced at the initial stage of hydrocarbon oxidation. We tried to apply the cross-correlation of OH and CH band luminescence intensity to the flame structure. The wavelength of 308 nm was selected for OH band emissions, and the wavelength of 431.5 nm was selected for CH band emissions. After collecting light by using a collecting lens (f=400mm), the light was separated with a dichroic mirror, transmitted through the interference filters, and was detected by photomultipliers. A water-cooled sampling probe with a suction hole of 0.3 mm diameter was used to measure the exhaust gas concentration, with variations of supplied equivalence ratios, Q_1 of the flow rate, and Q_2. The injected-unburned mixtures react first, then the unburned parts of the primary region react with the surrounding air. To prevent a secondary reaction, a duct was set. Its diameter was 250 mm and height 800 mm.

Experimental conditions for schlieren photography were the following : Φ_1 was 1.2 and Φ_2 were 0, 0.2, 0.4, and 0.6. Table 1 shows the turbulence characteristics of the unburned mixture.

Table 1 Experimental conditions for turbulence characteristics and combustion (flow rate unit : 10^{-3} m^3/s)

	Q_1	Φ_1	Q_2	Φ_2	Re
Case 1			0.0	—	15559
Case 2	1.35	1.2	1.12	0.2	41430
Case 3			1.66		59091

3. Experimental Results and Discussion

3.1 Flammable limit and stabilization

Figure 2 shows the distribution of lean flammable limits with the supplied equivalence ratio, Q_1 of the flow rate, and Q_2. Φ_0 is the total equivalence ratio for the total mixture (Q_1 plus Q_2). The direct photographs of each type of flame are also shown in Fig. 2. The flames were stable near a very rich condition in this experiment. Because the rich flammable limits were not important for this study, they were not discussed here. With increase in Q_1 for every condition, the lean flammable limits were decreased, but, with increase in Q_2 for the same Q_1 flux, they were extended to a very low equivalence ratio. For the conditions of $Q_1=1.35\times10^{-3}m^3/s$ and $Q_2=0.0$, the time-averaged flame was in round shape. The inflow of Q_1 made a recirculation zone after impingement. The flame was stabilized by recirculation. The thickness of the radial direction was approximately 65 mm. For the condition of $Q_2=1.12\times10^{-3}m^3/s$, the radial thickness of the flame was decreased, but the central and axial directional lengths of the flame luminescence became longer than that in $Q_2=0.0$ condition. These phenomena resulted from a depression in the flame with an inflow of Q_2 near the central axis. As the central

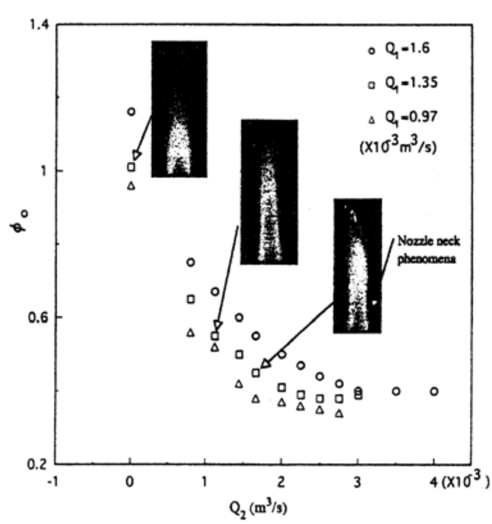


Fig. 2 Lean flammable limits and direct photographs

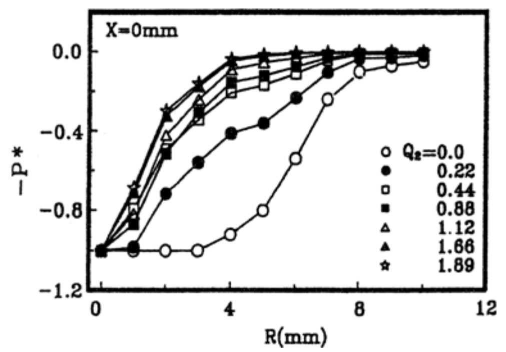


Fig. 3 Distribution of dynamic pressure with Q_2

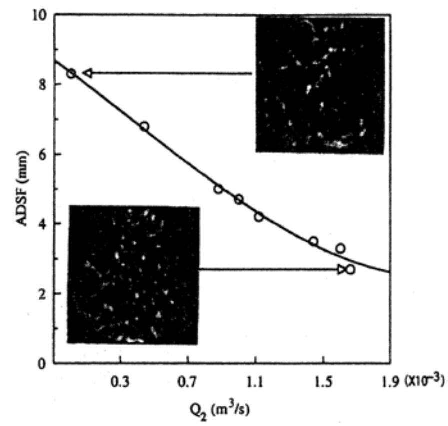


Fig. 4 Micro-schlieren images and the ADSF distribution

directional momentum was increased with Q_2, the flame zone moved downstream. For a higher flow rate of $Q_2=1.66\times10^{-3}m^3/s$, the area of flame luminescence decreased. In particular, there was a constrictly shaped flame, called nozzle-neck phenomena, near the nozzle exit. It was found that the very lean flame in the doubled jet burner was stabilized by the nozzle neck phenomena. As the flammable limit was extended to $\Phi_0=0.5$ in the condition of Q_2 over $2\times10^{-3}m^3/s$, the flame was stabilized even under the very lean conditions. This result was very simple and economical, compared to the method of extending the lean flammable limits with a heat recirculating combustor or a cyclone furnace.

Figure 3 shows the distribution of dynamic pressure around the nozzle exit with variations in Q_2 levels in the non-burning condition. It was well known that a high-pressure region became wide with increasing Q_2. The extension of the high-pressure region at the fixed step corresponded to the increase of the recirculation area. This enlarged recirculation area influenced the stabilization of the flame even at the very high speeds or under the lean conditions. The constricted region in Fig. 2 coincided with this extended high-pressure region.

3.2 Flame structure near the nozzle exit

It is well known that the blowout occurs when the flow speed of an unburned mixture is higher than the flame propagation rate and also when the flame near the flame attachment region oscillates greatly. The blowout velocity will increase when the flame zone thickness near the flame holder is thick and a flame consists of small-scale eddies.

Figure 4 shows micro-schlieren images and the ADSF distribution. The ADSF distribution does not indicate quantitative eddy scales, but enables qualitative discussions about the eddy scales near the nozzle exit. The flame structure is axisymmetric, and the optical axis is in a radial direction to the flame. The two reaction zones of ten averaged images under the same conditions were superimposed. The ADSF value decreased with increasing Q_2. It was found that the eddy scale with an increase of Q became smaller, due to strong turbulence. The ion currents, OH, and CH luminescence intensity were measured to investigate in detail the flame structure near the nozzle exit.

Figure 5 shows the auto-correlation of ion currents. Because the radial distributions were shown, each condition respectively represented the reaction characteristics in unburned, reacting, and burned regions. For Case 1, a prominent peak appeared at $\tau=0$, then a peak that had a relatively high correlation followed. If the width of the prominent peak were related to the flame zone thickness and an interval of prominence, and if the following peaks were related to the wrinkle period of the laminar flame, these characteristics would agree with the structure of a wrinkled laminar flame. The first duration that the auto-correlation function value falled at $1/e$ was 0.28 ms at R=7 mm. By multiplying the time of 0.28

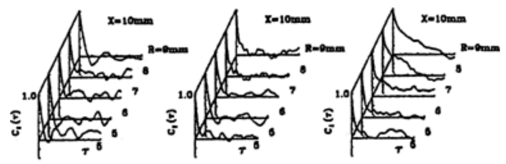

(a) Case 1 (b) Case 2 (c) Case 3

Fig. 5 Auto-correlation of ion currents

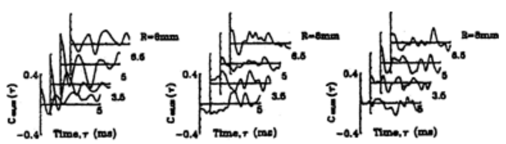

(a) Case 1 (b) Case 2 (c) Case 3

Fig. 6 Cross-correlation of OH and CH band luminescence intensity

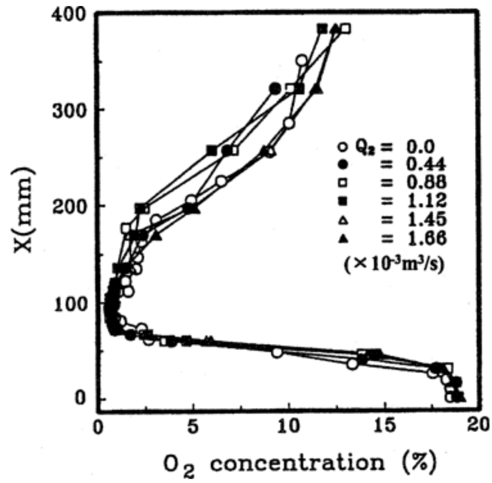


Fig. 7 Distribution of oxygen concentration levels

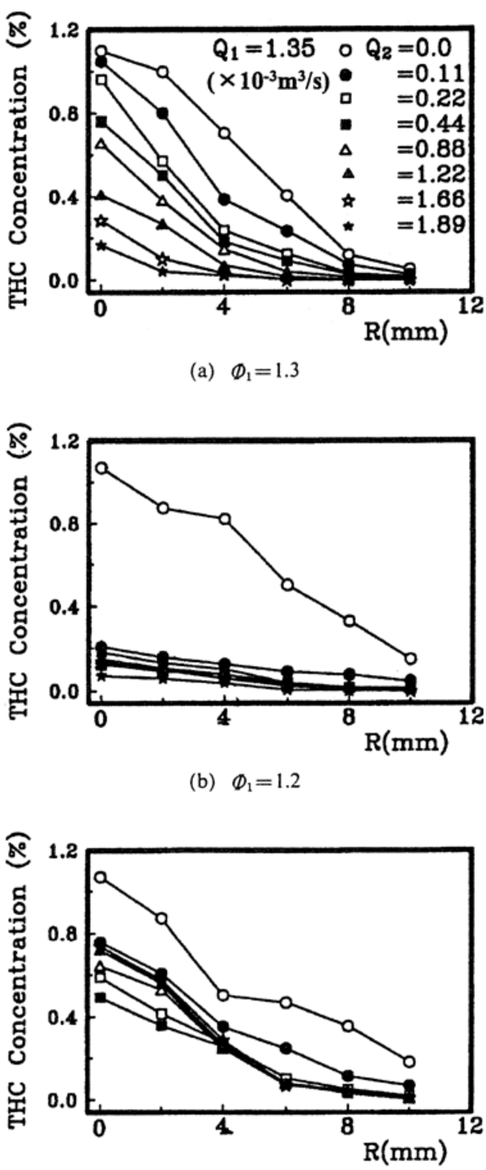
ms by the local flame front propagation velocity of approximately 9.375 m/s, a value of 2.625 mm was obtained. Considering the length of the electrostatic probe of 0.5 mm, the 2.625 mm thickness of the flame zone might be negligible. For Case 3, a prominent peak appeared at $\tau=0$. A correlative peak did not exist and decreased with high frequency oscillation. Therefore, the flame structure of Case 3 was quite different from that of Case 1, where a thin reaction zone passed periodically. Case 3 had a very thick flame zone that consisted of many small reacting eddies. The first duration at which the auto-correlation function value fell to 1/e was 0.56 ms at R=7 mm. By multiplying the time of 0.56 ms by the local flame-front-propagation velocity of approximately 25 m/s, a value of 14 mm was obtained. The flame in Case 3 was much thicker than that in Case 1.

Figure 6 shows the cross-correlation distribution of OH and CH luminescence intensity. For Case 1, a relatively high correlation peak appeared at $\tau=0$, even though there was some time delay. However, for Cases 2 and 3, the correlation was relatively weak. The flame in Case 1 was believed to be reacting in the thin reaction zone, but the flames of Cases 2 and 3 had very thick reaction zones that consisted of many small reacting eddies. It was concluded that a lean condition flame was stabilized by a thick flame zone that had small eddies. The existence of an increased high-pressure region, achieved with addition of Q_2, was effective in stabilizing a lean condition flame.

3.3 Variation of flame shapes with flux and equivalence ratio

Figure 7 shows the distribution of various levels of oxygen concentration with increasing Q_2 along the central axis. A duct was attached to a double jet burner to prevent mixing of Q_2 with the surrounding air Q_1. Φ_1 was 1.2, and Φ_2 was 0 at constant Q1 of 1.35×10^{-3}m^3/s. The flow rate of Q_2 varied from 0 to 1.66×10^{-3}m^3/s. The oxygen concentration was about 20% upstream of the flame under all conditions, and then it diminished slowly to a minimum value at the distance between 75 mm and 125 mm. It was found that combustion reaction seldom occurred at the region of minimum oxygen concentration. The increase in oxygen concentration of downstream was caused by mixing of Q_2 with surrounding air which was entrained. We measured the level of total hydrocarbon concentration (THC) at the region of minimum oxygen concentration to compare the results of combustion under various conditions.

Figure 8 shows a distribution of various levels of THC concentration along the radial direction with changing Q_2 levels. Q_1 was constant at 1.35×10^{-3}m^3/s. Φ_1 varied in the range of 1.1~1.3. The region of 1.1% THC concentration along the central axis was chosen as a measuring cross



(a) $\Phi_1=1.3$

(b) $\Phi_1=1.2$

(c) $\Phi_1=1.1$

Fig. 8 Distribution of THC concentration levels

-section. For Fig. 8(a) ($\Phi_1=1.3$), the level of THC concentration decreased with increasing Q_2, in spite of increase in the central direction momentum. Therefore, the burning velocity increased with increase in Q_2. The reduction in the level of THC concentration with increase in Q_2 coincided with improvement in combustion efficiency. For Fig. 8(b) ($\Phi_1=1.2$), the level of THC concentration decreased suddenly only in the case of a small influx of Q_2. It is well known that combustion efficiency can be improved with only a small flux of Q_2. It is not necessary to supply much more than a critical level amount of flux for high combustion efficiency. For Fig. 8(c) ($\Phi_1=1.1$), the level of THC concentration was lowest at $Q_2=0.44\times10^{-3}m^3/s$. In this case, the flame was somewhat unstable, and its length became shorter than the case without Q_2. However, as Q_2 was increased, the flame became stable, due to the nozzle neck phenomenon.

The influx of Q_2 had an effect on extending the lean flammable limits and on flame stabilization in the double jet burner. It was found that a suitable minimum flux of Q_2 appearing nozzle neck phenomena for a constant Q_1 existed. Therefore, the flame was unstable when the flux of Q_2 was under the critical value and the equivalence ratio of Φ_1 was relatively low.

4. Conclusion

This study estimated the lean flammable limit, flame stabilization, flame structure, and the burner characteristics under lean condition by using a doubled jet burner. The following conclusions were obtained:

(1) The lean flammable limit can be extended to a very low region in a double jet burner.

(2) A flame can be stabilized by the nozzle neck phenomena and a thick flame zone consisting of small eddies.

(3) The influx of Q_2 had an effect on extending the lean flammable limits and on flame stabilization.

References

Ballel, D. R. and Lefebvre, A. H., 1979, "Weak Extinction Limits of Turbulent Flowing Mixtures," *ASME Journal of Engineering for Power*, Vol. 101, pp. 343~348.

Choi, B. R., Choi G. M., and Chang I. G., 1996, "An Experimental Study on the Characteristics of Mixture and Flame Scale," *KSME(B)*, Vol. 20 -3, pp. 1040~1049.

Dearden, L. M., Massingham, J. D., Pourkashanian, M. , Wild, P. N., Williams, A., and Yap,

L. T., 1996, "Controlling NOx Emissions from High-Temperature Air-Preheat Burners with Air-Staging," *J. Inst. E.*, Vol. 69, pp. 23~30.

Dryer, M. J. and Crosley, D. R., 1985, "Fluorescence Imaging for Flame Chemistry," *Proceedings of International Conference Lasers '84*, pp. 211~218.

Furukawa. J, Harada. E, and Hirano. T, 1989, "Micro-Structure of High-Intensity Turbulent Premixed Flame," *JSME, Series II*, Vol. 55, pp. 3758~3765.

Haresty, D. R. and Weinberg, F. J., 1974, "Burners Producing Large Excess Enthalpies," *Combustion Science and Technology*, Vol. 8, pp. 201~214.

Kawamura, T., 1988, "An Experimental Study on Combustion of Ultra Lean Fuel and Air Mixture by Heat Recirculation," *Tran. JSME*, pp. 2575~2583.

Kido, H., Nakashima, K., Huang, S. and Kitano, K., 1990, "A Study on the Fine Structure of Propagating Turbulent Flames in Premixed Mixture," *JSME, Series II*, Vol. 33, No. 2, pp. 362~369.

Kotani, Y. and Takeno, T., 1982, "An Experimental Study on Stability and Combustion Characteristics of an Excess Enthalpy Flame," *Nineteenth Symposium (International) on Combustion, The Combustion Institute*, pp. 1503~1509.

Masters, J., Webb, R. J. and Davies, R. M., 1979, "The Use of Modelling Techniques in the Design and Application of Recuperative Burner," *J. Inst. Energy*, Vol. 52, pp. 196~204.

Takeno, T., Sato, K., and Hase, K., 1981, "A Theoretical Study on an Excess Enthalpy Flame," *Eighteenth Symposium (International) on Combustion, The Combustion Institute*, pp. 465~472.

Takeno, T. and Sato, K., 1979, "An Excess Enthalpy Flame Theory," *Combustion Science and Technology*, pp. 73~84.