초음속 공기장에서 Bluff-Body를 이용한 안정화염의 특성과 구조

김지호* · 윤영빈**†

The Characteristic Modes and Structures of Bluff-Body Stabilized Flames in Supersonic Coflow Air

Ji-Ho Kim* · Youngbin Yoon**†

ABSTRACT

Experimental investigations are performed on the stability and the structure of bluff-body stabilized hydrogen flames. The velocities of coflow air are varied from subsonic to supersonic velocity of Mach 1.8 and OH PLIF images and Schilieren images are used for analysis. Three characteristic flame modes are classified into three regimes with the variation of fuel-air velocity ratio; a jet like flame, a central-jet dominated flame and a recirculation zone flame. Stability curves are drawn to find the blowout regimes and to show that flame stability is improved by increasing the lip thickness of fuel nozzle that works as bluff-body. Damköhler number is adopted in order to scale the blowout curves of each flame obtained at different sizes of the bluff-body and all blowout curves are scaled successfully regardless of its bluff-body size.

Key Words : bluff-body stabilized flame, supersonic flame, flame stability, Damköhler number

1. Introduction

Bluff body nozzles are basic devices for stabilizing both premixed flames and non-premixed flames. The coflow air entrains part of the central fuel jet into low speed recirculation zone in the wake of bluff body and combustion mixing is accomplished for flame stabilization. With the existence of bluff body, the flame characteristics are changed from a pure diffusion flame classically stabilized on the burner surface to a partially premixed flame stabilized on the recirculation zone [1].

A number of researchers investigated the structure of bluff body stabilized flame and classified that flames[2~7]. They identified the relation between the flame structure and the flame stability

Furthermore, the bluff-body nozzles play an important role in stabilizing flames in supersonic coflow air [8]. However, few studies have focused on supersonic flames, especially bluff-body stabilized flames having high flow velocities up to supersonic condition [9~11].

Therefore, the present research has been performed in order to investigate the structures of unconfined hydrogen diffusion flames in supersonic (M=1.8) coflow air. The first objective of the present study is to define the stability limits of high-speed hydrogen flames. The second is to investigate the structure of hydrogen diffusion flames behind the bluff body on unconfined combustor by increasing the coflow air velocity from subsonic to supersonic regimes.

* 서울대학교 기계항공공학부 대학원
** 서울대학교 기계항공공학부
† 연락저자, ybyoon@plaza.snu.ac.kr

2. Supersonic combustor and conditions

Figure 1 shows the small-scale supersonic combustor. The supersonic air nozzle is designed by the characteristic method and manufactured so that the expansion ratio of the supersonic air nozzle (A_e/A^*) is 1.438 and the designed Mach number is 1.8. The fuel tube has an inner diameter($d_{F,i}$) of 1.04mm, an outer diameter($d_{F,o}$) of 9.52mm, and a length of 37cm such that the fuel velocity profile can be assumed to be a fully developed pipe flow. Hydrogen can be injected up to the sonic velocity of 1190m/s. The fuel mass flow rates are monitored by the use of calibrated choke orifice(diameter 0.4mm).

Fuel tubes with a thick lip are used in order to stabilize supersonic flames because the large size of the recirculation zones can be made behind the thick tube lip that acts as bluff body. When thicker fuel tube having fixed inner diameter($d_{F,i}$) and exit area for airflow is used, the velocity range of fuel and air for stable flames is expanded[12]. In this research, it was found that flames could be stabilized in the supersonic coflow condition (M=1.8) when the blockage ration ratio ($d_{F,o}^2/ d_A^2$) is greater than 0.84.

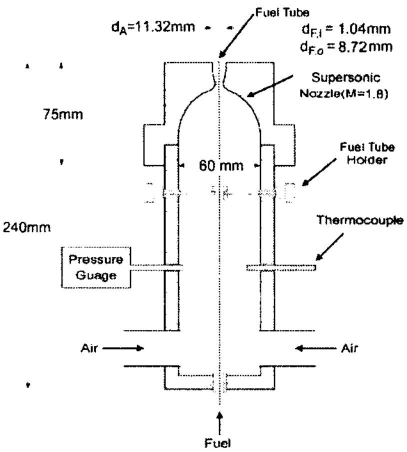

Fig. 1. Schematic of bluff-body combustor for hydrogen-air diffusion flame. Coflow air can be increased to Mach 1.8

3. RESULTS AND DISCUSSIONS

3.1 Stability curve of bluff-body stabilized flames

Figure 2 shows flame stability curves of bluff-body stabilized flame. It is known that there are two distinct lobes at the stability curve of this flame and each lobe is affected by different physical parameters, such as fuel nozzle lip size, coflow air temperature, fuel or air velocities[12]. In the present research, the tips of the lobes are not closed for the experimental limitation of flow rate in fuel and air. However, the shape of curves in low velocity ranges is similar to that of from Yoon et al. [12]. They defined two distinct limits: the far-field blowout limit of a lifted flame (horizontal limits in Fig.2), where the flame blows out after the flame lifts off and the near-field blow out limit (vertical limits in Fig.2), where the flame blows out suddenly and with no lift off.

Our interest in the present study, however, is the near-field blowout limit. It is noted that the near-field limit in Fig.2 occurs when the fuel flow rate is relatively small compared to the airflow and this lower fuel rate is an operation condition of most propulsion devices. The near-field blowout limit can be extended farther to large air velocities if a thick fuel tube is used. However, this distinct lobe-shape was not observed in many previous studies that employed a fuel tube having a sharpened rim. The far-field blowout of lifted flames is not of primary interest in the present study because it is impossible to obtain far-field blowout while maintaining supersonic air.

Table 1. Experimental conditions of coflow air at supersonic combustor exit plane (R_B= 0.636, $d_{F,i}$ = 1.04mm, $d_{F,o}$=8.72mm, d_A=11.32mm) with a fixed hydrogen fuel condition ($U_{m,F}$ = 620m/s, =0.043g/s, Re=6000, $T_{o,F}$ = 294K).

	case I	case II	case III$_a$	case III$_b$
total pressure of air [atm]	–	1.34	2.36	3.72
air mass flow rate [g/s]	–	2.3	9.1	18.2
air mass-weighted velocity [m/s]	–	42.5	190	380
coflow velocity	No coflow air	subsonic coflow air	supersonic coflow air	supersonic coflow air
classification of flame	jet-like flame (Regime I)	central jet dominated flame (Regime II)	recirculation zone flame (Regime III)	
flame type	pure diffusion flame	narrow-waist flame	open-tip flame	closed-tip flame

Table 2. Dimensions of fuel tubes and air nozzles at each blockage ratio. Inner diameters of fuel tubes and exit areas of coflow air are fixed.
($d_{F,i}$=1.04mm, $\pi(d_A^2-d_{F,o}^2)/4$ = 40.8mm^2)

blockage ratio (R_B), $(d_{F,o}/d_A)^2$	bluff-body diameter, $d_{F,o}$[mm]	diameter of air nozzle, d_A [mm]	lip thickness of fuel nozzle, $(d_{F,o}-d_{F,i})/2$ [mm]
0.496	7.14	10.14	3.05
0.546	7.92	10.72	3.44
0.596	8.72	11.32	3.85
0.636	9.52	11.94	4.24

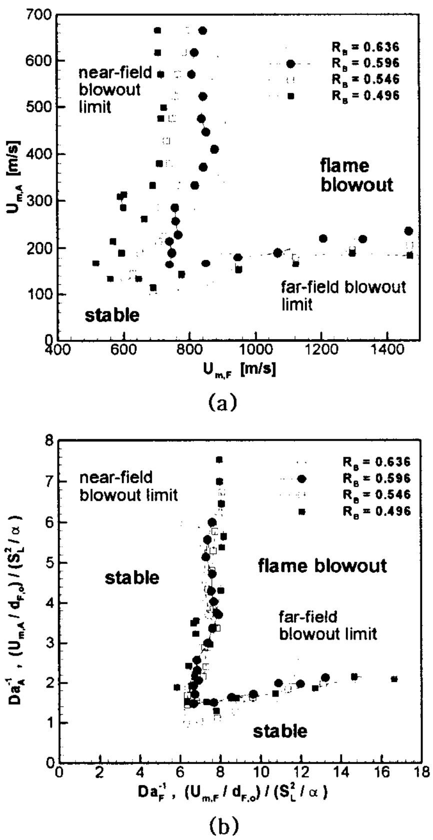

Fig. 2 (a) Flame stability curves of bluff-body stabilized flame by varying blockage ratio(R_B). (b) Normalized stability curves using Damköhler number based on mass weighted velocities of air and fuel.

Air and fuel velocities are generally used as variables in flame stability curves that indicate the flame-existing conditions and ranges. Instead, mass weighted velocities are used to extend this curve to supersonic range [12]. Figure 2(a) shows the stability curves of bluff-body stabilized flames when varying the blockage ration from 0.496 to 0.636, as listed in Table 2. Each fuel tube of combustors has different lip size, but the inner diameter of fuel tube is not changed to maintain the same condition for fuel jet. And the inner diameter of air nozzle is changed in order to maintain the area of airflow. Figure 2(a) indicates that the improved stability was achieved by increasing the outer diameter of the fuel tube in the near-field limit, that is, the increase of blockage ratio. The thicker fuel tube lip acts as bluff-body and provides a larger recirculation zone, where low speed flow exists and flame can be stabilized. However, far-field stability limit is not affected by the variation of blockage ratio because the behavior of lifted flames in the far-field is not affected by the outside geometry of fuel tube.

Basically, flame stability is not a critical phenomenon when the central fuel jet velocity is relatively low, i.e. when it is less than 500m/s. This implies that flame is stable at a large Damköhler number, which is defined as the characteristic time of flow divided by characteristic time of chemistry. Large Damköhler number implies a much larger characteristic flow time than the chemical time. If it is assumed that flame is blown out when the fuel flow escapes the recirculation zone before chemical reaction occurs, the Damköhler number of the fuel flow can be used as a criterion of flame blowout, which is defined as follows:

$$Da_F \equiv \frac{\tau_f}{\tau_c} = \frac{\textit{passing time of fuel jet through recirculation zone}}{\textit{chemical reaction time}} = \frac{d_{F,o}/U_{m,F}}{\alpha/S_L^2}$$

where the length of recirculation zone is assumed to be proportional to the bluff-body size. Also, Damköhler number of airflow is defined as follows:

$$Da_A \equiv \frac{\tau_f}{\tau_c} = \frac{\textit{passing time of coflow air through recirculation zone}}{\textit{chemical reaction time}} = \frac{d_{F,o}/U_{m,A}}{\alpha/S_L^2}$$

For the scaling of the stability limits in

Fig.2(a), the inverse Damköhler number of fuel and air was used and Fig.2(b) was obtained. Chemical reaction time was obtained from simple analysis as follows:

$$\tau_c = \frac{\delta}{S_L} = \frac{\alpha / S_L}{S_L} = \frac{\alpha}{S_L^2}$$

where flame thickness (δ) is scaled with α / S_L. Laminar flame velocity (S_L) of hydrogen is set to be 210cm/s at room temperature and pressure and thermal diffusivity (α) of air is 5.89×10^{-4} m^2/s at 2000K[17]. It is found that the flames are blown out at higher Da_F^{-1} and Da_A^{-1} (lower Da_F and Da_A): the values of these limits of Da_F^{-1} and Da_A^{-1} are approximately 7 and 2, respectively, which correspond to the values of 0.14 and 0.5 for Da_F and Da_A, respectively.

3.2 Combustion diagram for bluff-body stabilized flames

Figure 3 is the combustion diagram showing different regimes for bluff-body stabilized non-premixed flame. The blockage ratio of this flame is 0.596. A parameter $\gamma = U_{m,A}/U_{m,F}$ is defined as the velocity ratio between air and fuel streams based on the mass flow rates. The classification of our research is based on the criteria of Chen et al. [5] who defined the flame regimes and stability curves in the subsonic flame by using LPG gas as fuel. By varying parameter γ, three characteristic stable flame modes can be found in Fig. 3: jet like flame (Regime I), central-jet dominated flame (Regime II), and recirculation zone flame (Regime III) having open-tip or closed-tip. The typical shapes of flames, having the conditions denoted as case I, II, III_a and III_b, are shown as photographs, schilieren images, OH PLIF images in Fig.5 and 6. The γ_u limit (triangle symbol) is at the border line between Regimes II and III and the γ_l limit (inverse triangle symbol) is at the border line between Regime I and II. In the present study, the values of γ_u limit and γ_l limit are about 0.2 and 0.06, respectively. The γ_u value is measured accurately, but the γ_l value drawn approximately in order to show the transition of flame modes from Regime I to II. The shapes of combustion diagrams for the other three bluff bodies are qualitatively similar to each other. Although the general trends in Fig. 3 are consistent with previously proposed diagrams [4,5], it is intended to identify the combustion mechanism of bluff body stabilized hydrogen flames that is obtained with a large range of coflow air varying from zero to supersonic velocities.

Generally, hydrogen fuel has large flame velocity because of short induction time and large value of heat of formation. Therefore, hydrogen flames can be maintained at broad velocity ranges up to supersonic flows when compared to the experiments of other researchers using hydrocarbon fuel [3, 5]. In the present experiment, the flame stabilization at higher flow velocity can be attributed to the high blockage ratio and energetic hydrogen fuel. When the fuel jet has a much higher momentum (Regime I), central fuel jet penetrates through the recirculation bubble. When the fuel jet and annular air momentums are comparable to each other (Regime II), a central-jet dominated flame can be developed. This mode of flame is characterized as a narrow-waist flame. When the fuel jet momentum is too weak to penetrate the recirculation bubble (Regime III), all fuel mass will be retained behind the bluff body to form a recirculation zone flame. Especially, in the present study, Regime III is divided into two modes: open-tip flame and closed-tip flame.

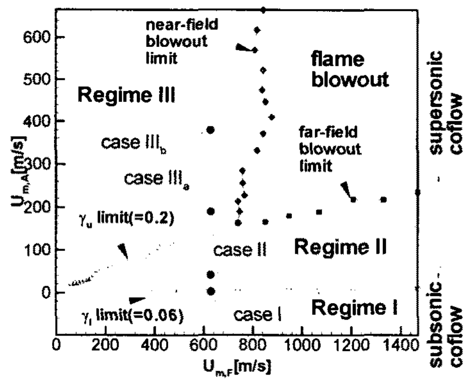

Fig. 3. Combustion diagram of bluff-body stabilized flames: jet-like flame (Regime I), central jet-dominated flame (Regime II), and recirculation zone flame (Regime III). The γ_u limit and γ_l limit are about 0.2 and 0.06, respectively.

3.3 Effect of coflow velocity on supersonic flames

The visible length of the supersonic flame is a measure of the fuel-air mixing rate, that affects the flame stability process. Rapid mixing produces a short flame, whereas a long flame has stoichiometric contours further downstream where reduced strain rates occur. Figure 4 shows the variation of flame length by increasing air mass-weighted velocity. Flame length normalized by the inner diameter of fuel tube and air mass weighted velocity are on the y-axis and x-axis, respectively. Similar trends are found for each fuel velocity conditions of 115, 227 and 620m/s. At all the fuel velocity conditions, flame lengths have minimum values at the same air velocity of $U_{m,A}$ = 150m/s that is near the transition condition from subsonic to supersonic.

In the subsonic coflow ranges, the flame length is decreased significantly with increasing air velocity. However, in the supersonic ranges, the flame length is increased slowly and then eventually reaches to each length limit. This phenomenon can be attributed to the air-entrainment of subsonic flow and the compressibility effect of supersonic flow. Four points indicated in Fig.4 show the flame lengths corresponding to each condition of case I, II, III_a and III_b, the condition of which is shown in Table 1. Because these conditions represent the typical characteristics of each flame, various visualization methods are used to analyze the structure of the flames.

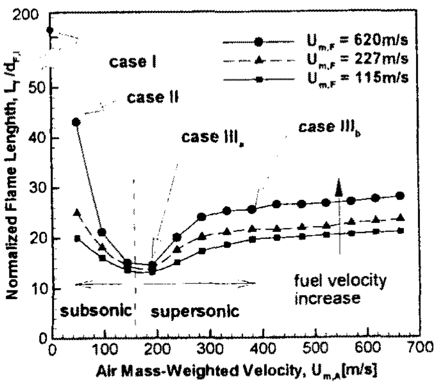

Fig. 4. Effect of coflow air on the length of hydrogen diffusion flames.

3.4 Structure of bluff-body stabilized Flame

Direct photographs and schilieren photographs for the four cases are shown in Fig.5. In order to investigate the flame structures with the change of air velocity, the hydrogen fuel velocity is fixed at 620m/s and Reynolds number of fuel is about 6,000. Case I is the pure diffusion flame that has no coflow air as shown in Fig.5(a). As the air velocity is increased slowly from zero to the value near the condition of case II, the flame shape is changed to the narrow-waist flame as shown in Fig.5(b). At the narrow waist of the flame, a high strain rate zone is brought by the strong entrainment of high speed coflow air. The high strain zone decreases the reaction rates and thus local extinction occurs.

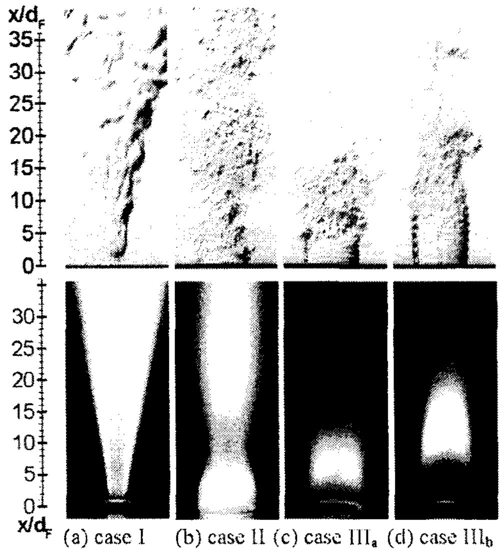

Fig. 5. Typical images of four stable modes of H_2 diffusion flames with annulus blockage ratio of 0.596 (top, exposure time = 1msec), direct photographs (bottom, exposure time = 0.5sec); (a) jet like flame (γ=0.0) (b) central-jet dominated flame (γ=0.068) (c) recirculation zone flame jet with open-tip (γ=0.306) (d) recirculation zone flame jet with closed-tip (γ=0.613).

When fuel-air velocity ratio γ exceeds 0.2, jet-dominated flame of Regime II is changed to recirculation zone flame of Regime III. As air velocity is increased to case III_a that is the transition condition from subsonic to supersonic flames, the flame starts to shrink and finally reaches extinction in the upper part of narrow waist. This can be attributed to the large amount of air entrainment to the flame. In this condition, the flame has the shortest length and shows open-tip shape as shown in Fig.5(c).

As the velocity of air is further increased as shown in case III_b of the supersonic flame, the flame becomes longer and thinner with closed-tip shape and a slightly lifted flame is formed as shown in Fig.5(d). From the schilieren photographs of Fig.5(c) and Fig.5(d), the airflow fields are shown to be supersonic as indicated by the existence of shock waves. The over expanded shock structure of airflow can be found at the bottom of the flame in case III_a of Fig.5(c) and this supersonic region is elongated in case III_b where airflow rate is increased.

It is noted that the flames in cases I, II and III_a are attached to the base of fuel nozzle as indicated by the red glow color at the exit of fuel nozzles as shown in Fig.5(c), whereas the flame in case III_b is slightly lifted from the base. This may be due to the supersonic annular coflow at the base of flame, where compressibility effect of supersonic flow may reduces the mixing of fuel and air to a certain extent.

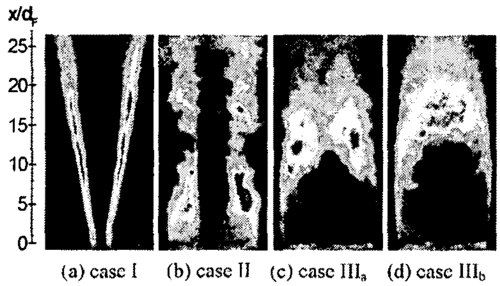

Fig. 6. OH PLIF Images of H_2 diffusion flames with different coflow air velocities.

PLIF image of OH radical is captured for these conditions of flames. Figure 6(a) is OH PLIF image of pure diffusion flame (case I), which shows the reaction zone along the shear layer between fuel jet and ambient air. Figure 6(b) shows the characteristics of turbulent diffusion flame in the subsonic coflow air condition (case II). The OH radicals are concentrated along the boundaries between the fuel and air. Local extinction is found in the narrow waist of the flame (at x/d_F = 12). From Fig.6(c), the OH radicals are found to be near the tip of the flame and the flame looks like an open-tip flame (case III_a), whereas the high intensity region of OH radicals moves to the center of the flame resulting in a closed-tip flame (case III_b) as shown in Fig.6(d). This case III_b exemplifies the typical characteristics of partially premixed flame with a supersonic coflow air condition.

In the flame with subsonic coflow of case II, the reaction regions are found at the bottom of flame and shear layer between fuel and air, which shows that the flame occurs from the broad area of recirculation zone. However, in the flame with supersonic coflow of case III_b, the reacting core is found at the center of flame and the low intensity of reaction region is observed near the recirculation zone at the bottom of the flame, which suggests that the structure of supersonic flame differs from that of subsonic flame; supersonic flame anchors at the outer edge of the outside recirculation zone near the exit of the bluff-body fuel nozzle as suggested by other researchers [13, 14] and active reaction occurs at the end position of shock structure as shown in Figs.5(c) and (d).

4. CONCLUSIONS

Experiments have been performed to investigate the structure of bluff-body stabilized hydrogen flame with high-speed coflow air varying from subsonic to supersonic velocities of up to Mach 1.8. Stability curves are drawn to find the blowout regimes and it is found that flame blowout stability is improved by thicker fuel nozzles which work as bluff-body. Damköhler number is introduced here in order to explain the flame blowout characteristics at the different scale of bluff-body, and it is found that flame is blown out when Da falls short of certain values (Da_F < 0.14 and Da_F <0.5). The flame stabilization modes are classified into three regimes: (i) jet-like flame, (ii) jet dominated flame, and (iii) recirculation zone flame. The upper and lower limits of air-velocity ratios (γ_u, γ_l) are used as criteria of flame mode.

From the flame length variation curves, it is found that flame lengths, independently to the fuel velocity, have minimum values at the same air velocity of 180m/s that is close to the transition condition from subsonic to supersonic speed. The subsonic flame length decreases with increasing air velocity, whereas the supersonic flame length increases with air velocity and finally reaches certain value limits. In subsonic coflow ranges, the coflow air is entrained to the fuel jet and the mixing of fuel and air is increased. Therefore, the flame length is reduced with increasing air velocity. However, once the air coflow reaches the supersonic condition, the mixing is not dependent on the entrained air, but the mixing is controlled by the increased compressibility effect.

The structure of flames are illustrated by various means, including direct photographs, schilieren photographs, Mie scattering and OH PLIF images. OH PLIF image of recirculation zone flame having supersonic coflow shows that the reaction zone exists at the downstream side of recirculation zone. However, in the central-jet dominated flame having subsonic coflow, the reaction zone exists at the inside of recirculation zone. Also, recirculation zone flame of Regime III can be divided into two modes: open-tip flame and closed-tip flame. The open-tip flame was changed to the closed-tip flame with the increase of coflow air, which is assumed to be interrelated with the increased compressibility effects.

Acknowledgement

The others gratefully acknowledge the finance support, provided under the grant No. 98-0200-04-01-3 from the Basic Research program of KOSEF and the grant No. M1-0104-00-0058 from the National Research Laboratory program of the KISTEP.

References

[1] Esquiva-Dano, I., Nguyen, H. T. and Escudie, D., "Influence of a Bluff-Body' s Shape on the Stabilization Regime of Non-premixed Flames," Combust. Flame 127:2167-2180 (2001).

[2] Roquemore, W. M., Britton, R. L., and Sandhu, S.S, AIAA J. 21:1410 (1981).

[3] Masri, A. R. and Bilger, R.W."Turbulence Diffusion Flames of Hydrogen Fuels Stabilized on a Bluff Body," Proc. Combust. Inst., Vol. 20, pp. 319-326 (1984).

[4] Huang, R. F. and Lin, C. L., Combust. Sci. Technol. 100:123-139 (1994).

[5] Chen, Y.-C, Chang, C.-C., Pan, K.-L., and Yang, J., "Flame Lift-off and Stabilization Mechanisms of Nonpremixed Jet Flames on a Bluff-body Burner," Combust. Flame 115:51-65 (1998).

[6] Chin, L.P. and Tankin, R.S., Combust. Sci. Technol. 80:207-229 (1991).

[7] Masri, A.R., Kelman, J.B., and Dally, B.B., Proc. Combust. Inst., Vol. 27, pp. 1031-1038 (1998).

[8] Law, C. K., Major Research Topics in Combustion (Hussani, M. Y., Kumar, A., and Voigt, F.G., Eds.), Springer-Verlag, New York, 1992, pp. 201-236

[9] Cheng, T. S., Wehrmeyer, J. A., Pitz, R. W., Jarrett, O. Jr., and Northam, G. B., Combustion and Flame, Vol. 99, pp. 157-173 (1994).

[10] Driscoll, J. F., Huh, H., Yoon, Y., and Donbar, J. M, Combust. Flame 107:176-186 (1996).

[11] Bryant, R. A., Ratner, A., and Driscoll, J. F., AIAA paper 99-0445 (1999).

[12] Yoon, Y., Donbar, J. M., and Driscoll, J. F., Combust. Sci. and Technol. 97: 137-156 1994).

[13] Badrinarayana, M. A., J. of the Royal Aeronautical Soc. 65:475 (1961)

[14] Wagner, B. and White, R. A, AIAA J. 18:876 (1973)