Non-premixed Hydrogen Flame Structure in Supersonic Coflowing Air Flows

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ABSTRACT

Experiments have been performed to investigate the structure of axisymmetric hydrogen diffusion flame in a supersonic coflow air. The characteristics and structure of supersonic flames are compared with those of subsonic flames as the velocity of coflow air increases from subsonic to supersonic velocity of Mach 1.8. Also, the subsonic and supersonic flow fields are analyzed numerically for the non-reacting conditions and the possible flame contours indicated by fuel mass fraction are compared with the measured OH radical distributions. It is found that the flame structure indicates more like a partially premixed flame as the coflow air velocity is increased from subsonic to supersonic regimes; strong reaction zone indicated by intense OH signal is found at the center, which is different from subsonic flame cases. And it is shown that the fuel jet passes along the recirculation zones behind the bluff-body fuel nozzle resulting in relatively long mixing time. This is believed to be the reason of the partially premixed flame characteristics found in the present supersonic flames.

Keywords : supersonic flame, partially premixed structure, recirculation zone, OH PLIF

INTRODUCTION

As the need for hypersonic civilian and military aircraft increases, the new concepts for hypersonic propulsion systems have been proposed. One of them is a scramjet (supersonic combustion ramjet) engine using hydrogen fuel since the hydrogen is preferred as the main fuel due to large energy per mass. Because the residence time of fluid is as short as several millisec in scramjet engines, the main topic in supersonic combustion research is focused on enhancing fuel-air mixing and maintaining flame stability in supersonic flows[1]. In order to investigate the mixing process and flame stability, it is necessary to understand the flame structure in supersonic air flows.

However, few studies have focused on the structure of supersonic flames and the difference between subsonic flame and supersonic flames. Cheng et al.[2] measured the temperature and the concentration of several species in a supersonic combustor using UV Raman scattering and LIPF(Laser Induced Predissociative Fluorescence). They reported that more turbulent fluctuations were found in supersonic flames than in subsonic flames and strong reaction occurred in the upper part of flames. Driscoll et al.[3] found the factors that affect the flame length in a confined combustor. They showed that the lengths of supersonic flames were smaller than those of subsonic flames under the certain ranges of velocity and density ratios and the flame lengths were decreased as $U_F\rho_F/U_A\rho_A$ were increased.

Bryant et al.[4] investigated the detailed flame structure between subsonic and supersonic flames using OH PLIF images in a confined combustor. They found that OH signal was concentrated downstream of the supersonic flame and the high strain rates played an important role in fuel-air mixing at the base of flames. However, the influence of shock waves generated by the change of cross section area in a confined supersonic combustor cannot be avoided.

Therefore, the present research has been performed in order to investigate the structure of hydrogen diffusion flames in a supersonic (M=1.8) coflow air excluding the effect of shock waves using an axisymmetric unconfined combustor. The objectives of this study are to investigate the structure of hydrogen diffusion flame in unconfined combustor by increasing the coflow air velocity from subsonic to supersonic regimes and to find the reasons why the characteristics of the partially premixed flame in a supersonic case are found.

EXPERIMENTS AND ANALYSIS METHODS

The supersonic combustor used in this research is composed of a fuel nozzle of 9.52mm outer diameter and 1.08mm inner diameter, which is concentric to the supersonic air nozzle. The supersonic air nozzle are designed by the characteristic method and manufactured so that the supersonic air nozzle expansion ratio(A_e/A^*) is 1.483 and the designed Mach number is 1.8. The Mach number of fuel tube exit is expected to be unity due to the frictional choking.

Thick lip fuel nozzles were used in order to stabilize supersonic flames since they provided the large size of recirculation zone behind the bluff body nozzle[5]. In this combustor geometry, flames can be stabilized in the supersonic region when the fuel nozzle lip thickness ratio($(d_o-d_i)/d_i$) is over 5, where d_o and d_i indicate the outer and inner nozzle diameters, respectively. Thus, the lip thickness ratio was

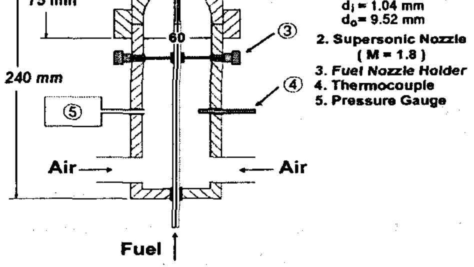


Fig. 1. Schematic of supersonic combustor

selected to be 9.15 in the present research.

Table 1 shows the conditions used in the experiment. Case I, where the total pressure is 1.34 atm, indicates a subsonic flow condition at the air nozzle exit since the total pressure is not high enough so that an air flow is decelerated by normal shock waves generated downstream of the air nozzle throat. In this case, the subsonic flame characteristics are observed. At higher total pressure of 3.72 atm, case III provides a nearly fully expanded condition. The supersonic flame characteristics are found in case III. Case II allows the transition condition from subsonic to supersonic flames.

Table 1. Experimental conditions of air at supersonic combustor exit plane (d_F=*1.08mm*, $d_{F,O}$=*9.52mm*, d_A=*11.94mm*) with a fuel condition is fixed ($\dot{m}_F$= 0.043 g/s, M_F = 1.0, $T_{o,F}$ = 300K)

	case I	case II	case III
Mach number	0.52	1.8	1.8
Total pressure [atm]	1.34	2.36	3.72
Mass flow rate [g/s]	2.3	9.1	18.2
Velocity [m/s]	34.4	486	486
Total temperature [K]	300	300	300

RESULT AND DISCUSSIONS

Flame Lengths and Shapes

Figure 2 shows the variation of flame length normalized by the fuel tube diameter. When the air mass flow rate increases, the flame length is decreased significantly in the subsonic regions. However, in the supersonic regions, the flame length normalized by the fuel tube diameter is increased slowly and then stays about a constant value of 28 as a length limit. Three points indicated in Fig. 2 show the flame lengths corresponding to cases I, II and III, respectively.

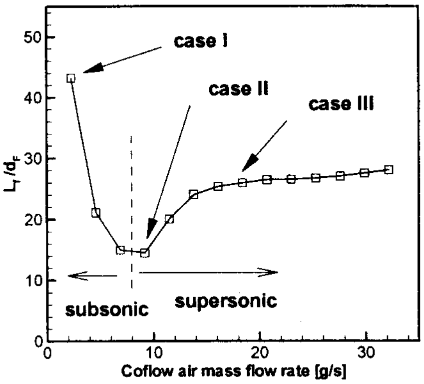
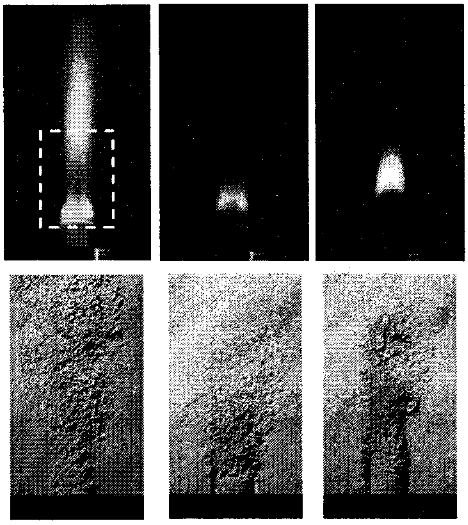


Fig. 2. Variation of flame length as a function of coflow air mass flow rate

Direct photographs and schilieren photographs for three cases are shown in Fig. 3. In order to obtain the flame in case I, the mass flow rate of 0.043g/s hydrogen fuel was supplied and then ignited. Finally, the air mass flow rate was increased slowly up to the point as shown in Table 1. As the total pressure is increased and thereby the mass flow rate of



(a) case I (b) case II (c) case III

Fig. 3. Images of H_2 diffusion flames with coflow air: direct photographs (top) and spark schilieren images (bottom)

coflow air is increased, the condition of case I is achieved. As the air is entrained to the middle of flames, the narrow waist near the subsonic flame base is found as shown in Fig. 3(a) with a dotted line. This is attributed to the decreased reaction rates caused by high strain rates. As the coflow air is increased near case II, the flow reaches a supersonic condition and the flame length is decreased by a factor of 4. This is believed to be due to the large amount of air entrained to the flame in case II. At this conditon, the flame has the shortest length and shows open-tip shape as shown in Fig. 3(b).

As the mass of air is increased further in case III, the flame becomes longer and thinner with closed-tip shape as shown in Fig. 3(c). From the schilieren photograph of Fig. 3(c), the flow fields are shown to be supersonic and slightly over-expanded shock waves are observed. Beyond the condition of case III, the flame lengths are almost constant regardless of the amount of air mass flow rates.

It is noted that the flames in cases I and II are attached to the base of fuel nozzle as indicated by the red glow color at the exit of fuel nozzle in Fig. 3(b), whereas the flame in case III is slightly lifted from the base. This may be due to the fact that the larger mass flow rate of coflow air disturbs the velocity fields of the recirculation zone so that the flame anchored zone moves downstream of the fuel nozzle.

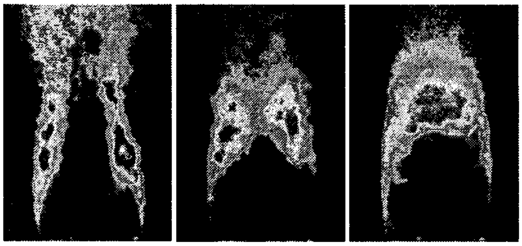

(a) case I (b) case II (c) case III

Fig. 4. OH PLIF Images of H_2 diffusion flame with coflow air, for (a) case I, (b) case II, and (c) case III

The size of OH PLIF images as shown in Fig. 4 corresponds to the region enclosed by white dashed line in Fig. 3(a). Figure 4(a) shows the characteristics of turbulent diffusion flame in the subsonic air flow condition of case I. The OH radicals are concentrated along the boundaries between fuel and air. Since the amount of entrained air to the fuel is not enough to dilute the fuel within the size of OH images in case I, the flame tip is shown to be located further downstream of this image. However, the OH radicals are found to be near the tip of flame and look like an open-tip flame in case II as shown in Fig. 4(b), whereas the high intensity region of OH radicals moves to the center of flame resulting in closed-tip flame in case III as shown in Fig. 4(c). Therefore, it is found that the structure of flame in supersonic coflow air is not the same as that of subsonic case due to the amount of air entrained to the flame. It may be suggested that the structures of flame in supersonic coflow in cases II and III are similar to the partially premixed flame with reacting core at the center, contrary to the subsonic diffusion flame with coflow air.

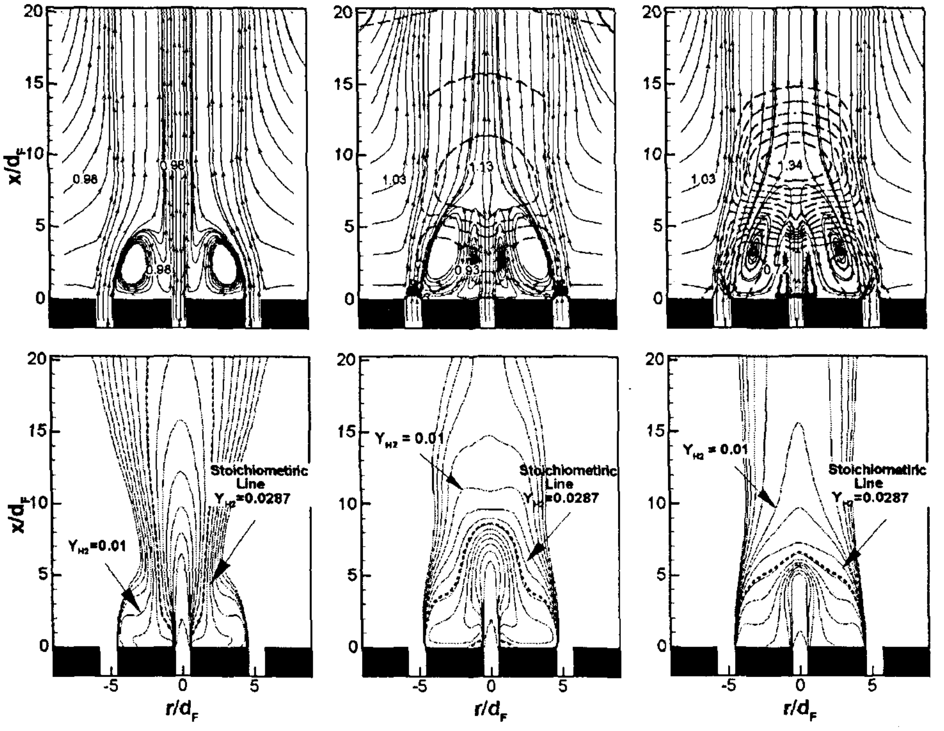
Partially Premixed Zone

Figure 5 is the numerical results simulating the mixing of hydrogen jet and coflow air without chemical reactions. Top figures show pressure contours (thick dashed line) and stream lines (thin solid line). Bottom figures represent hydrogen mass fraction contours (thin solid line) and stoichiometric line (thick dashed line) of $Y_{H2}=0.0287$. As the coflow air is entrained to the fuel jet, the hydrogen fuel is mixed with air so that the 'Partially Premixed Zone(PPZ)' can be formed.

Also, the PPZ can be defined according to the fuel mass fraction for convenience; the partially premixed zone may be defined as the area between 1% hydrogen mass fraction contour (Y_{H2}=0.01) and stoichiometric line in order to match this zone with the flame contours indicated by the OH radicals in Fig. 4. Even though the numerical results are simulating the non-reacting cases, they show good agreement with direct photographs in Fig. 2. The narrow waist in the subsonic case I and the flame length in the supersonic cases II and III.

In case I(Fig. 5(a)), the coflow air jet having relatively small momentum moves toward centerline along the outer stream of recirculation zone, and then abruptly changes its direction when it meets fuel jet. This may cause a large strain rate in this point (i.e. flame waist). Consequently, this high strain rate makes the flame to be almost extinct locally and thus low reaction rate zone occurs.

Although the pressures in case I are relatively uniform throughout the flame zone, the slightly high and low pressure zones are found in case II and III; i.e., the low pressure zone (0.72~ 0.93atm) exists near the exit of fuel nozzle and the high pressure zone (1.34~ 1.13atm) is located at the downstream of the end of recirculation zone along the core of the flame. The fuel jet expands abruptly as it passes through low pressure zone first and then loses its momentum by colliding with the high pressure zone. Thus, the fuel jet follows the boundary of recirculation zone rather than it directly passes through the high pressure



(a) case I (b) case II (c) case III

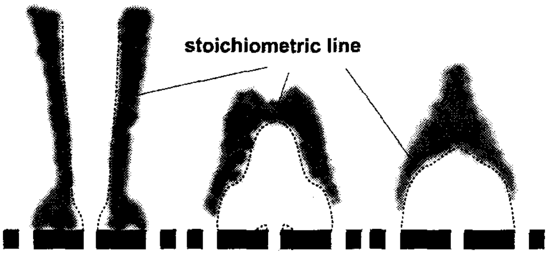
Fig. 5. Simulation of H_2-air mixing for case I, II and III : stream line and pressure contour (top) and fuel mass fraction and stoichiometric line(bottom)

zone. Hence, the fuel jet stays relatively long time near the exit of fuel nozzle so that the fuel can have more chance to mix with the air entrained along the recirculation zone. This may be the reason of the characteristics of partially premixed flame found in cases II and III. Also, the momentum increase of coflow air jet increases the size of recirculation zone where the flame can be stabilized in supersonic air flow.

In case II(Fig. 5(b)), the height of stoichiometric line is decreased significantly as the mass flow rate of coflow air increased. In case III, compared with case II (subsonic case), the height of stoichiometric line is reduced more, whereas the height of 1% line(Y_{H2}=0.01) is slightly increased at the center of fuel nozzle. Thus, the height between the stoichiometric line and the 1% mass fraction of hydrogen line is increased as the mass flow rate of coflow air increases in the supersonic region, which means that the luminous visible flame zone may look longer in case III than that of case II. This may be explained by the reason as follows; as the coflow air is entrained to the fuel, the flame length of subsonic flame is getting shorter.

However, once the air coflow reaches the supersonic stream, the mixing between fuel and air is not related to the amount of entrained air only since the mixing in supersonic flows is known to be insufficient so that the 1% mass fraction of hydrogen line is found further downstream of the fuel nozzle in case III. Thus, the visible flame zone in case III is shown to be thicker and elongated, which is also observed by the direct flame photography in Fig. 3.

It is interesting to note the shape of 1% mass fraction of hydrogen line in cases II and III; the flat top shape in case II is changed to the steep and sharp hat shape in case III. This may be due to the inferior mixing characteristics in supersonic flows since the broader regions near the center of the fuel are exposed to the supersonic coflowing air. Thus, the mixing of fuel with air in case III is believed to progress slowly compared to case II.



(a) case I (b) case II (c) case III

Fig. 6. Expected flame zone (0.01<Y_{H2}<0.028) which is defined as 'Partially Premixed Zone'

Donbar et al.[6] simultaneously captured images of CH radical and OH radical and showed that thinner CH layer is located at fuel rich side and thicker OH layer is found at fuel lean side. The partially premixed zone, which is defined in terms of the mass fraction of fuel, can be assumed to be a reacting zone as predicted by the numerical simulation. Thus, the flame front can be expected with the fuel mass fraction and is shown in Fig. 6. The expected flame front shape in each case shown in Fig. 6 agrees well not only with the shape in the direct photographs in Fig. 3., but also with the OH radicals in Fig.4 even though it is obtained in the non-reacting case.

The narrow and long mixing layer is shown in the subsonic flames of case I, where mixing is achieved through molecular diffusion around the fuel and air jets and momentum exchange among small eddies. However, the mixing zones are getting to merge together in case II as the mass flow of coflow air is increased. Finally, the intense mixing or reaction zones are found at the center core in case II with supersonic coflow air; the flame with supersonic coflow air is shown to behave as the partially premixed flame.

CONCLUSION

Experimental and numerical investigations on hydrogen diffusion flames with supersonic coflow air are presented. The structure of flame is illuminated using various methods, including direct photographs, schilieren photographs, and OH PLIF images. Then, the flame contour indicated by OH radicals may be related to the 'partially premixed zone (PPZ)', which is defined from the fuel mass fraction in non reacting conditions; the PPZ indicates the area between stoichiometric line and 1% mass fraction of hydrogen obtained from numerical simulation. Also, The transition of flame structure is observed when the mass flow rate of coflow air increases.

In the supersonic flame, the fuel jet loses its momentum due to the high pressure zone and thus it moves along the recirculation zone. Therefore, the fuel has long characteristic time for mixing, which is believed to be the reason to show the characteristic of partially premixed flames rather than non-premixed flames.

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