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EFFECT OF AIR STREM MACH ON MIXING FIELD IN A SUPERSONIC COMBUSTOR

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ABSTRACT
A numerical study on mixing of hydrogen injected into a supersonic air stream has been performed by solving Two-Dimensional full Navier-Stokes equations. An explicit Harten-Yee Non-MUSCL Modified-flux-type TVD scheme has been used to solve the system of equations, and a zero-equation algebraic turbulence model to calculate the eddy viscosity coefficient. The main objectives of this study are to increase the mixing efficiency and the flame holding capability of a supersonic combustor. The performance of combustor has been investigated by varying the air stream Mach number, keeping constant the backward-facing step height and other calculation parameters. The results show that small Mach number causes good mixng of hydrogen and oxygen in upstream recirculation region, but penetration height is low in downstream. In moderate Mach number large and elongated upstream recirculation causes high prenetration dominated by convection of recirculation. The increase of Mach number causes higher penetration of hydrogen. High Mach number increases both the mixing efficiency and flame holding capability.

1. INTRODUCTION
Mixing of fuel with oxidizer and their combustion are encountered in many engineering applications. Particularly, the fuel injection in both supersonic and hypersonic streams requires special attention for efficient mixing and stable combustion. Though a considerable number of researches have been carried out on mixing and combustion of fuel with supersonic air stream, still it faces many unresolved problems. The main problems that arise in this regard, concern mixing of reactants, ignition, flame holding, and completion of combustion. More investigations are required to overcome these problems. In fact, in supersonic combustion, high penetration and mixing of injectant with main stream is difficult due to their short residence time in combustor. In an experimental study, Brown et al. [1] showed that the spreading rate of a supersonic mixing layer decreased drastically with increasing free stream Mach number. A similar conclusion was drawn by Papamoschou et al. [2] on the basis of a theoretical analysis of shear-layers. Furthermore, they showed that the reduction in spreading rate correlated most closely with the convective Mach number, where convective Mach number is defined as the differential velocity normalized by the speed of sound. An independent linear stability theory analysis of Ragab et al. [3] reached the same conclusion. These investigations showed that difficulty exists in achieving a high degree of mixing in high Mach number flows. Therefore, it is necessary to investigate all the parameters that affect the mixing of hydrogen in supersonic airstreams. This study is a part of M.Sc. thesis done by Hoque [4]. Here the effect of air stream Mach number on mixing and flame holding capability in supersonic stream is investigated. The geometric configuration of the calculation domain and the inlet conditions of main and injecting flows are shown in Fig.1. The left boundary consists of a backward-facing step of height 5-mm, which was found most efficient in mixing by Ali [5] among the conditions investigated. For this study, the air stream Mach number is varied by taking as 3.00 (Case 1), 3.25 (Case2), 3.50 (Case3), 3.75 (Case4) and 4.0 (Case5). The inlet widths of air and side jet are used as Ali et al. [6], which showed good performance on mixing.

2. MATHEMATICAL DESCRIPTION
The flow field is governed by the unsteady, two-dimensional full Navier-Stokes and species continuity equations. The body forces are neglected. With the conservation-law form, these equations can be expressed by

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=\frac{\partial F_v}{\partial x}+\frac{\partial G_v}{\partial y} \qquad (1.1)$$

Where

$$U=\begin{pmatrix}\rho\\ \rho u\\ \rho v\\ E\\ \rho Y_i\end{pmatrix},\ F=\begin{pmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ (E+p)u\\ \rho Y_i u\end{pmatrix},\ G=\begin{pmatrix}\rho u\\ \rho uv\\ \rho v^2+p\\ (E+p)v\\ \rho Y_i v\end{pmatrix}$$

$$Fv=\begin{pmatrix}0\\ \sigma_x\\ \tau_{xy}\\ \sigma_x u+\tau_{yx}v-q_x\\ -\dot{m}_x\end{pmatrix},\ G_v=\begin{pmatrix}0\\ \tau_{yx}\\ \sigma_y\\ \tau_{xy}u+\sigma_{yv}-q_y\\ -\dot{m}_x\end{pmatrix}$$

$$p=\sum_{i=1}^{ns}\rho_i R_i T=\sum_{i=1}^{ns}\rho_i \frac{R}{W_i}T, \qquad (1.2)$$

$$E=\sum_{i=1}^{ns}\rho_i h_i-\sum_{i=1}^{ns}\rho_i \frac{R}{W_i}T+\frac{\rho}{2}\left(u^2+v^2\right),$$

$$=\sum_{i=1}^{ns}\rho_i C_{pi} T-\sum_{i=1}^{ns}\rho_i \frac{R}{W_i}T+\frac{\rho}{2}\left(u^2+v^2\right), \qquad (1.3)$$

$$\sigma_x=\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+2\mu\left(\frac{\partial u}{\partial x}\right) \qquad \sigma_y=\lambda\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)+2\mu\left(\frac{\partial v}{\partial y}\right)$$

$$\tau_{xy}=\tau_{xy}=\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right), \quad \lambda=-\frac{2}{3}\mu \qquad (1.4)$$

3. RESULTS AND DISCUSSION

The present study consists of five cases varying air stream Mach number. The results are to be analyzed and discussed under the following contents: (i) The effect of Mach number on penetration and mixing of hydrogen, and (ii) The characteristics of the flow field.

3.1 Penetration and Mixing of Hydrogen

Figure 2 shows the penetration and mass concentration of hydrogen in the flow field. Different penetration height can be found at both upstream and downstream of different cases. Cases 1 and 2 show good mixing of hydrogen and oxygen in upstream recirculation region, but penetration height is low. For high Mach number (cases 3 and 4), large and elongated upstream recirculation causes high penetration dominated by convection of recirculation. At the same time due to strong interaction, high gradient of hydrogen mass concentration exists causing high penetration of hydrogen. It can be point out that the increase of Mach number causes higher penetration of hydrogen. This can be explained by the fact that the increase of Mach decreases the air inlet pressure, which helps the expansion of side jet resulting in high penetration. Figure 3 shows the mixing efficiency along the length of physical model for different cases . The figure shows that mixing efficiency increases sharply at injector position for all cases. Generally in upstream region, the increasing rate of mixing is moderate and in downstream it is slow. Individually, case 5 (Mach 4) has the highest increment of mixing efficiency both at the upstream region and injector position due to strong upstream recirculation and high interaction between air stream and side jet. Again case 5 shows that in upstream the increment of mixing along the length of physical model is highest, whereas in downstream the increment of mixing is slow and almost equal for all cases caused by the supersonic nature of flow. On the top of injector the increment of mixing efficiency of case 5 is higher than cases 1~4. Including the effects activated for mixing, case 5 has the highest overall mixing efficiency at the outflow boundary.

3.2 Characteristics of the flow field

Various characteristics phenomena such as separation shock, bow shock, Mach disk, reattachment shock can be seen in figure 4 (a~e) and 5 (a~e). Figure 4 (a~e) shows the pressure contours by which the pressure distribution and different shocks can be understood. Flow separation is initiated by the backward facing step at left boundary. The deflection angle of air stream increases with the increase of Mach number caused by the decrease of air inlet pressure. The under expanded side jet rapidly expands and forms a Mach disk and a bow shock due to the interaction with main flow. For high Mach number the slope of the bow shock is steeper indicating strong interaction between the main and side jet resulting in the high gradient of mass concentration and consequently high mixing efficiency. The maximum pressure and temperature in the flow field rises immediately behind the intersection of separation shock and bow shock. In the downstream region the reattachment shock is more visible in the pressure contour as shown in Fig. 4 (a~e). The pressure is higher in the upstream recirculation region while it is much lower immediately behind the injector caused by the suction of injection. Figure 5 shows the temperature contours for the cases (Case 1~5). The maximum temperature, found for cases 1, 2, 3, 4 and 5 are 2233 , 2335, 2467, 2561 and 2698 K, respectively. It can be pointed out that case 5 has the highest temperature which is caused by the interaction of side jet with high momentum of main flow. The separation shock, bow shock and Mach disk can also be understood from the Fig.5 (a~e). The temperature is lower at the upper part of the flowfield for all cases and at the upper left corner the temperature is the lowest.

4. CONCLUSION

The Mach number of air stream is varied as (3, 3.25, 3.5, 3.75 and 4) to investigate the mixing flow field. High penetration of hydrogen increases the mixing efficiency along the injector position. It is found that strong interaction is occurring between the main and injecting flows for high Mach number (M=4). High Mach number increases both the mixing efficiency and flame holding capability. So air stream in supersonic flow having Mach number 4 might act as a good flame holder and become efficient in mixing.

5. FIGURES

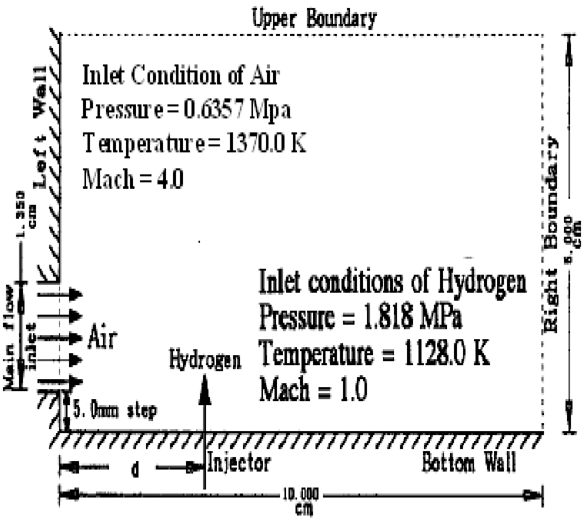

Fig.1 Geometric configuration

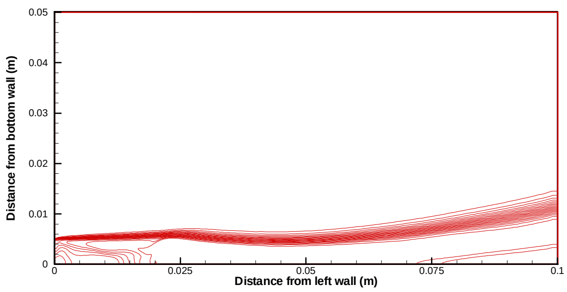

Fig.2(a) Case-1(Mach No. = 3)

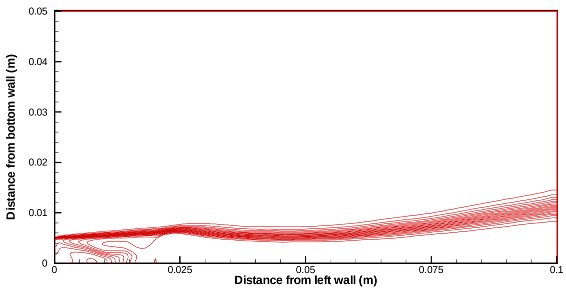

Fig.2(b) Case-2(Mach No. = 3.25)

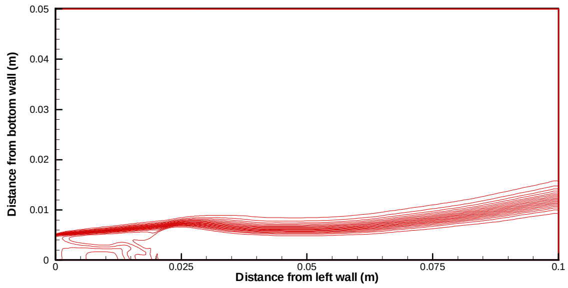

Fig.2(c) Case-3(Mach No. = 3.5)

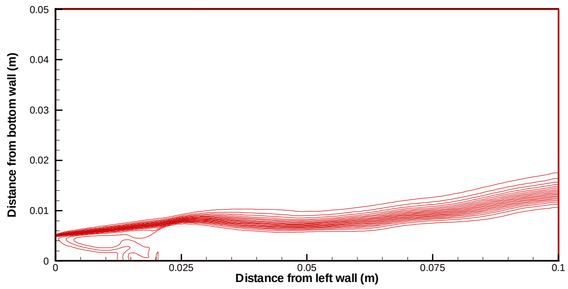

Fig.2(d) Case-4(Mach No. =3.75)

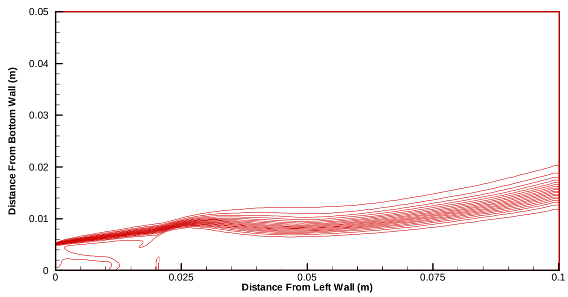

Fig.2(e) Case-5(Mach No. = 4)

Fig. 2 Mole fraction counter of Hydrogen, Φ(0.05, 1.0, 0.05);

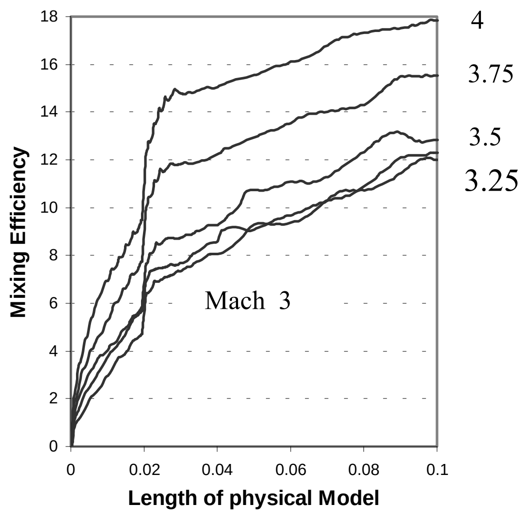

Fig. 3 Mixing efficiency along the length of physical model

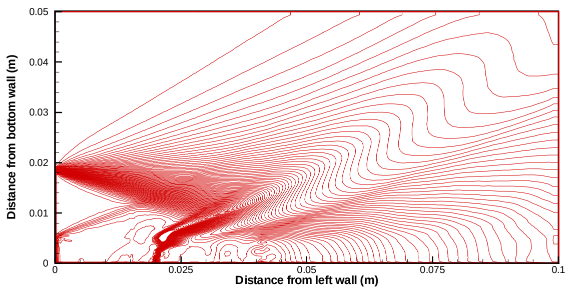

Fig. 4(a) Pressure contour Case-1(Mach No. = 3)

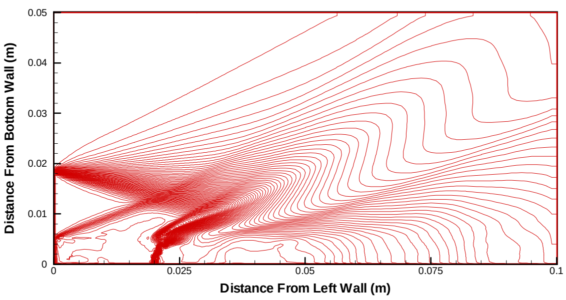

Fig. 4(b) Pressure contour Case-2(Mach No. = 3.25)

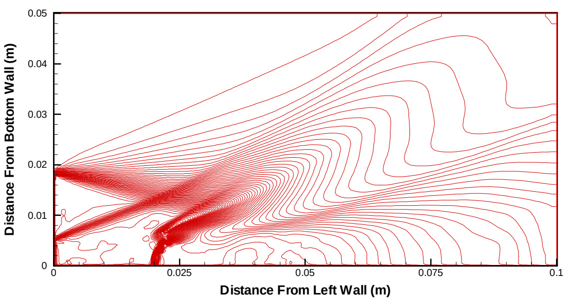

Fig. 4(c) Pressure contour Case-3(Mach No. = 3.5)

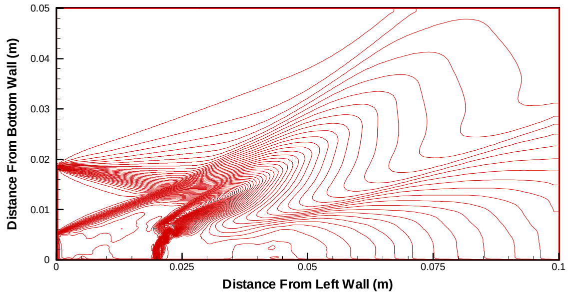

Fig. 4(d) Pressure contourCase-4(Mach No. = 3.75)

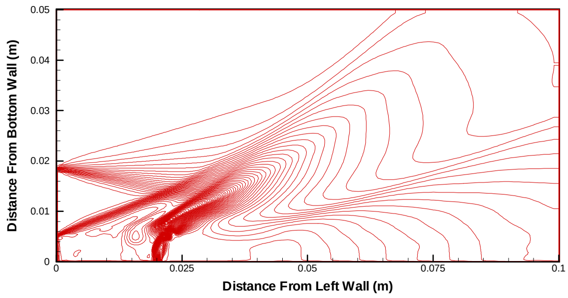

Fig 4(e) Pressure contourCase-5(Mach No. = 4)

Fig 4(a~e) Pressure (Pa) contour, Φ(2*104, 2*106, 2*104)

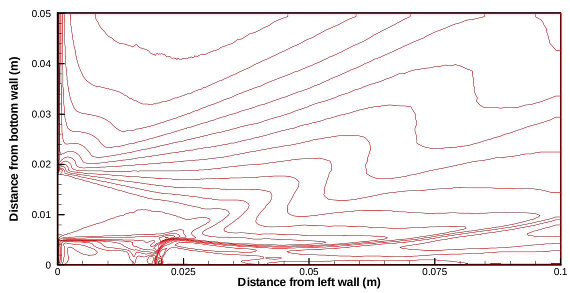

Fig. 5(a) Temperature contour Case-1(Mach No. = 3)

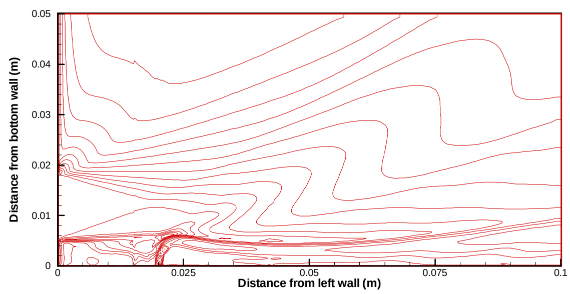

Fig. 5(b) Temperature contour Case-2(Mach No. = 3.25)

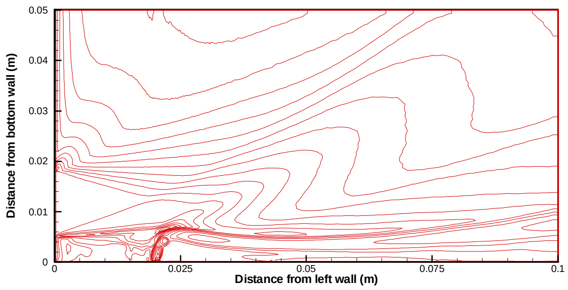

Fig. 5(c) Temperature contour Case-3(Mach No. = 3.5)

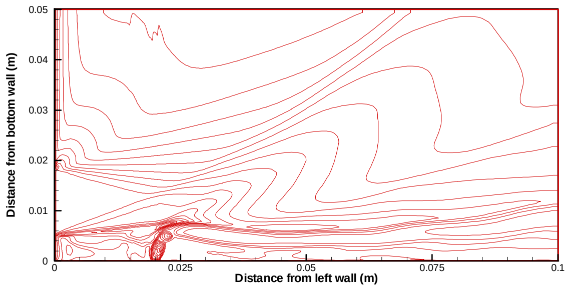

Fig. 5(d) Temperature contour Case-4(Mach No. = 3.75)

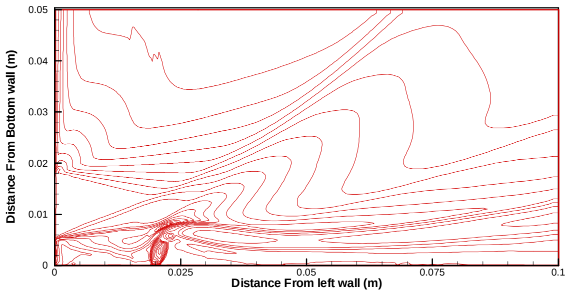

Fig. 5(e) Temperature contour Case-5 (Mach No. = 4)
Fig. 5 Temperature (K) contour, Φ(250, 2550, 100)

6. REFERENCES

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7. NOMENCLATURE

Symbol	Meaning	Unit
T	Temperature	(K)
E	Total energy	J/m^3
P	Pressure	(Pa)
F	Flux vector in x-direction	
G	flux vector in y-direction	
$F^\wedge$	Fransformed flux vector in ξ-direction	
U	Contra variant velocity in ξ-direction	
u	Horizontal velocity	m/sec
v	Vertical velocity	m/sec