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NUMERICAL STUDY ON MIXING FLOW FIELD WITH DIFFERENT ANGLES INTO A SUPERSONIC FLOW

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ABSTRACT
This paper investigates the performance of fuel combustion with the help of computer based simulation system. The simulation is carried out using huge volume of data analysis. 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 injection angle, keeping constant the backward-facing step height and other calculation parameters. The investigation shows that, small and large injecting angles increase the flame holding capability but mixing efficiency is poor. For moderate injecting angle, the configuration might act as a good flame holder and become efficient in mixing.

Keywords: Navier-Stokes Equations, Flame, Mixing Efficiency, Mach no

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. As

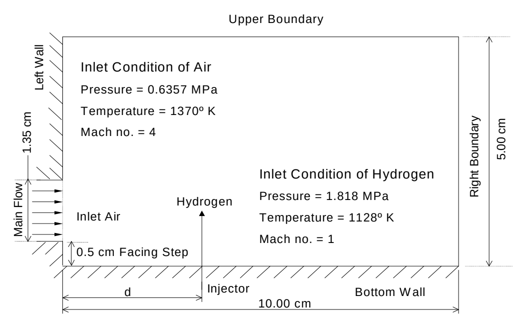


Fig 1. The geometric configuration of the calculation domain

an injectant, gaseous hydrogen is used because it is the most suitable fuel and has high potential of heat release. This is why a considerable number of researches [4-5] has been performed their investigations using hydrogen as an injectant. Therefore, it is necessary to investigate all the parameters that affect the mixing of hydrogen in supersonic airstreams. There exist several methods of fuel injection in the supersonic air stream. Perpendicular injection causes rapid mixing of injectant with main stream and is used to some degree at all flight Mach numbers to promote mixing particularly in upstream portion of the combustor. This study is a part of M.Sc. thesis done by Hoque [6]. Here the effect of injecting angle is investigated for a constant mach number. The geometric configuration of the calculation domain and the inlet conditions of main and injecting flows is shown in Fig. 1. In this investigations all cases, the left boundary of domain consists of a backward facing step of height 5 mm, a main flow inlet of height 0.9 cm and a solid wall of height 3.6 cm. The backward facing step of 5 mm used because it was found most efficient in mixing investigated by Ali et al [7]. Using Mach 4 we varied the angle 30˚, 60, 90˚, 120˚and 150˚.

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

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

The different terms of this equation can be found in Hoque et al [8].

3. RESULTS AND DISCUSSION

Results of varying angle are to be analyzed and discussed under the following contexts; (i) penetration and mixing of hydrogen under the variation of these parameters and (ii)characteristics of the flow field.

3.1 Penetration and Mixing of Hydrogen

Figures 2(a~e) show the penetration and mass concentration of hydrogen in the flow field. The difinition of "penetration" is given earlier. Penetration and mixing of hydrogen in a numerical simulation can occur by means of (i) turbulence and convection due to recirculation and velocity of the flow (ii) molecular diffusion. For all cases (case 1 ~ 5) the mole fraction contours of hydrogen are concentrated in a narrow region on the top of the injector, as shown in figure 2(a~e), which might became a high heat release zone in the reacting flowfield. The backward facing step associated with upstream recirculation brings the injectd hydrogen up to the left boundary in all cases. The hydrogen penetation height at different downstream locations can also be compared from Fig 2(a~e). Longer recirculation zone containing stoichiometric mixture strength results in a longer residence time and leads

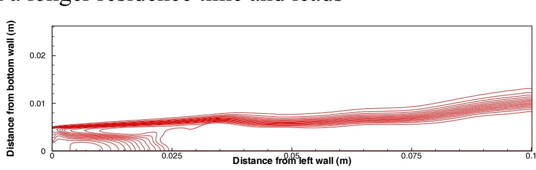


Fig 2a. Mole fraction counter of Hydrogen, Φ(0.05, 1.0, 0.05); Case-1(θ=30°)

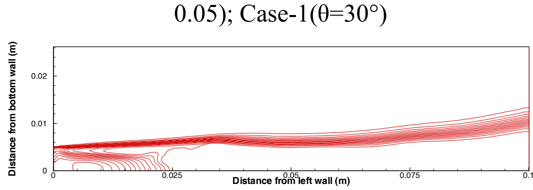


Fig. 2b. Mole fraction counter of Hydrogen, Φ(0.05, 1.0, 0.05); Case-2(θ=60°)

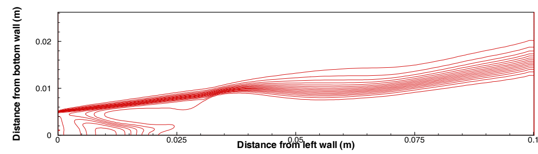


Fig 2c. Mole fraction counter of Hydrogen, Φ(0.05, 1.0, 0.05); Case-3(θ=90°)

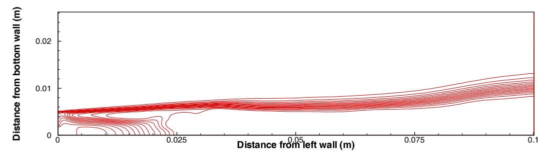


Fig 2d. Mole fraction counter of Hydrogen, Φ(0.05, 1.0, 0.05); Case-4(θ=120°)

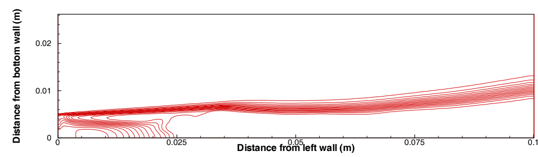


Fig 2e. Mole fraction counter of Hydrogen, Φ(0.05, 1.0, 0.05); Case-5(θ=150°)

to a more stable flame. Accordingly case-3 (θ=90^o) and 4 (θ=120^o) have good flame holding capability, because they can produce larger and elongated upstream recirculation where most of the region contains good proportion of hydrogen and oxygen exists. Again in cases having θ = 30^o and 150^o upstream region contains lower mass cencentration of hydrogen which is not good for flame holding. In downstream hydrogen distribution is seemed to be better in case 3~4 as mentiond earlier because of higher exparision of side jet.

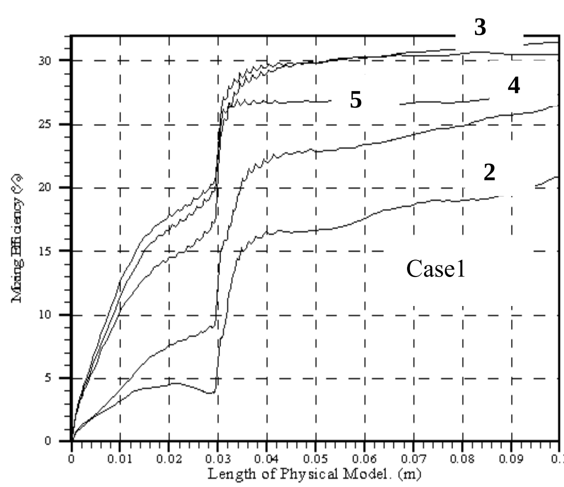
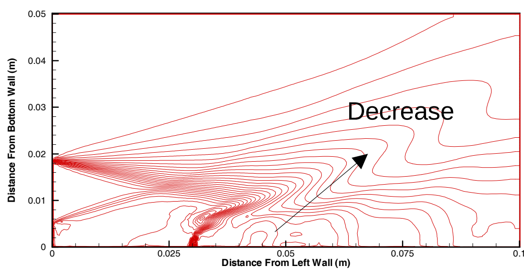


Fig 3. Mixing efficiency along the length of physical model

Figure 3 shows the mixing efficiency along the length of physical model for different cases (case 1~5). Physically mixing efficiency indicates the ratio of hydrogen mass flow rate capable of burning to its total mass flow rate at the exit of side jet. Figure 4 shows that mixing efficiency increases sharply at injector position of respective cases. Generally, in upstream region, the increasing of mixing is moderate and in downstream it is very slow. Individually, case-3(θ=90°) and 4(θ=120°) have the highest increment of mixing efficiency at injector position due to strong upstream recirculation. In downstream the increasing rate of mixing along the length of physical model for case-3(θ=90°) is higher than case-4 (θ=120°) whereas for case 5(θ=150°) it remains almost constant which indicates that for case 5. The larger combustor might increase the cost of construction of combustor provided the other parameters are identical. So case 3(θ=90°) has the maximum increasing rate of mixing in downstream.

3.2 Characteristics of the flow field



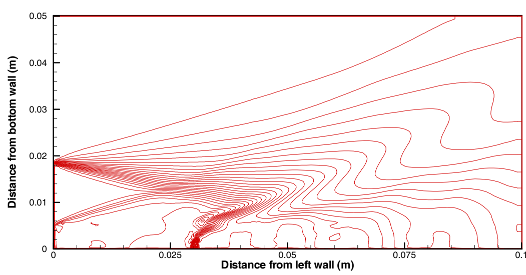
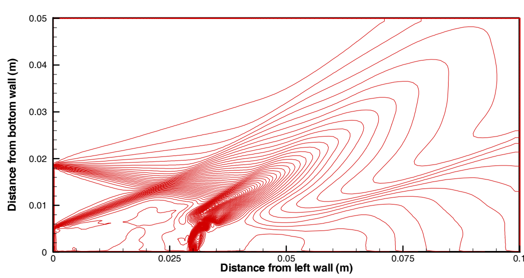


Fig 4a. Case-1(θ=30°)
Fig 4b. Case-2(θ=60°)



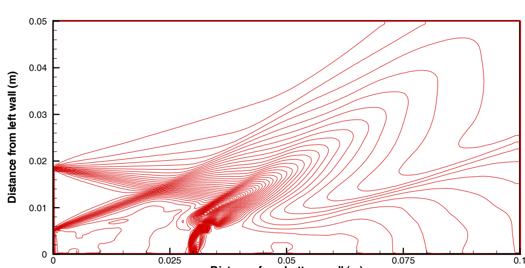


Fig 4c. Case-3(θ=90°)
Fig 4d. Case-4(θ=120°)

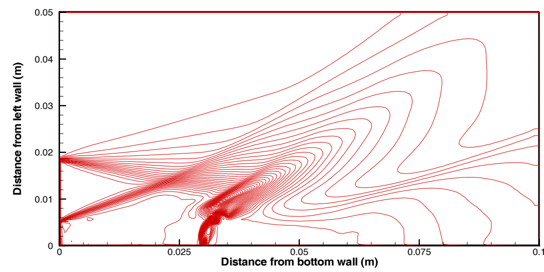


Fig. 4e. Case-5 (θ=150°)

Fig. 4 Pressure (Pa) contour, $\Phi(2*10^4, 2*10^6, 2*10^4)$

The characteristics of the flow field are shown in figs. 4 (a~e). For case 3 (θ=90°) the pressure in the downstream is relatively lower, at upper part of the flow field. Various characteristic phenomena such as separation shock, bow shock, Mach disk, reattachment shock can be seen in figures. The figure 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 main flow is deflected upward by the existence of wall at the upper part of the left boundary. The deflection angle is maximum for case 3(θ=90°) caused by strong interaction. Under expanded side jet rapidly expands and forms a Mach disk and a bow shock due to the interaction with main flow. This increasing Mach disk is caused by higher expansion of side jet. For the injecting angle θ=90° the slope of the bow shock is stepper indicating high interaction between the main and side jet. Due to strong interaction, high gradient of mass concentration exists and this indicates more uniform mixing. The maximum pressure and temperature in the flow field rises immediately behind the inter section of separation shock and bow shock. In the downstream region the reattachment shock is more visible in the pressure contour of figure 4 (a~e). The reattachment shock starts more or less at the same point for all cases (case 1~4). The pressure is higher in the upstream recirculation region while it is much lower immediately behind the injector caused by the suction of injection

4. CONCLUSION

The investigation showed that for varying injector angle small and large injecting angles have no significant upstream recirculation. Upstream recirculation is dominant for moderate injecting angle. Perpendicular injection angle increases the both mixing efficiency and flame holding capability. Small injecting angle and very large injecting angle have good flame holding capability but mixing efficiency is poor. It has been found out that for moderate injecting angle (θ=900) the combustor might act as a good flame holder and become efficient in mixing.

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