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MIXING OF SUPERSONIC JETS WITH DIFFERENT MERGING ANGLES FOR CONSTANT INLET PRESSURE AND VELOCITY

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ABSTRACT
In present investigation mixing of two supersonic non parallel gaseous streams has been simulated numerically. The streams are of air and hydrogen, which come into contact after passing over a finite thickness base. The gases are considered to be fed from a high-pressure reservoir. Two-dimensional unsteady state Navier-Stokes equations, energy, mass diffusion and species continuity equations are numerically simulated to analyze two-dimensional shear layers in supersonic flow field. An explicit Harten-Yee Non-MUSCL Modified flux-type TVD (total variation diminishing) scheme has been used to solve the system of equations. An algebraic turbulence model was used to calculate the eddy viscosity coefficient. Keeping constant the inlet pressure and velocity of the streams, the merging angle is varied to observe the physics of the mixing flow fields, mixing of shear layers and mixing efficiency. The result shows that when merging angle increases interaction between two streams increases and high momentum exchange occurs and eventually high mixing occurs for the pressure ratios considered here.

Keywords: Supersonic Combustor, Mixing, Shear Layers, Merging Angle

1. INTRODUCTION
Turbulent mixing layers occur in flow fields of many engineering applications e.g., combustion chambers, pre-mixers for gas turbine combustors, chemical lasers, propulsion systems and flow reactors. Particularly, the mixing of reactants and their complete combustion in supersonic combustion ramjet (scramjet) engines has drawn special attention of present scientists. In supersonic combustion systems, the flow speeds are so high that the fuel and oxidizer have little time to mix. The shear layers are naturally unstable and usually lead to a large scale mixing. The higher the Mach number, the longer length it takes the shear layers to become unstable. This reduces mixing accomplished in a given length. Several configurations of combustor have been studied to seek the enhancement of mixing. Generally parallel, normal or oblique type mixing is used. Most of the researchers studied two parallel supersonic streams.

Guirguis et al. [1] performed two-dimensional time-dependent numerical simulation of the mixing of two supersonic parallel streams of air. They simulated a supersonic shear layer in a two dimensional channel, 20 cm long and 2.4 cm high. They used flux corrected transport algorithm and neglected all diffusion transport processes. They considered only inviscid or convective mixing. They compared the vorticity, density and pressure contour of confined and unconfined shear layer. Farouk et al. [2] performed numerical simulation of the mixing of two supersonic streams of air. They simulated 25cm x 3cm flow field. Brown et al. [3] experimentally investigated the effects of density ratio on plane turbulent mixing between two streams of different gases. It was observed that, for all ratios of densities in the two streams, the mixing layer was dominated by large coherent structures. These structures made convection at nearly constant speed, and increased their sizes and spacing discontinuously by the process of amalgamation with neighboring ones. Thus these structures would grow in large scale and roll up in coherent manners that greatly increase the mixing surface. Finally it was concluded that large changes of the density ratio across the mixing layers have relatively small effect on the spreading angle, when one stream was supersonic. Papamoschuo et al. [4] observed that the spreading rate was dependent of Mach number but independent of transverse density gradients. This was in agreement with the experimental results of Debieve et al. [5] on different aspects of supersonic turbulent flows.

Gai et al. [9] experimentally studied the development of large-scale organized motions in compressible mixing layers. The mixing layer was formed behind the base of a parallel strut with a Mach 2 air stream and a co-flowing two dimensional slot jet of helium at a Mach number of 1.2. They observed that the thickness of the primary boundary layer had a strong influence on the growth and structure of the mixing layer. They showed that the injector lip could have significant effect on the subsequent flow development. Gerlinger et al. [10] found that increase in injector lip thickness resulted in increased shear layer thickness and also total pressure losses because of the stronger recompression shocks. They also found that increase in mixing layer thickness did not have significant effect on the mixing efficiency. In another investigation Guirguis et al. [11] studied the effect of bluff center bodies on mixing enhancement in supersonic shear layers. They observed that the shear layer became unstable faster than with the streamlined body. As a result, a large amount of convective mixing occurred within the length of the domain. Azim et al. [12] investigated plane mixing layers from parallel and non-parallel merging of two streams. The authors reported that both types of mixing layers were found to decrease in growth with increasing velocity ratio, though they spread more at the high speed side.

The air stream is at the upper side of the base plate whereas the hydrogen stream is underneath the base plate as shown in Fig.1. After separating from the base, the streams form shear layers and mix with one another. The length and width of the calculation domain is chosen to be 0.208m and 0.024m, respectively. In this study the effect of merging angles on the physics of fluid dynamics and mixing efficiency is studied. The merging angles are varied from 0 ~ 20º with the increment of 5º. The calculations of flow field with different merging angles are denoted as case 1 (merging angle 0º), case 2 (merging angle 5º), case 3 (merging angle 10º), case 4 (merging angle 15º), and case 5 (merging angle 20º). For all cases the pressure of both streams is considered as 1.0 atmosphere. The objectives of this investigation are (i) to increase the mixing efficiency of a supersonic combustor and (ii) to study the physics of fluid dynamics including shocks and turbulence. The results and discussion are presented in the following articles: (i) the physics of free shear layer (ii) mixing of hydrogen with air stream (iii) identification of the parameters that affect the free shear layer growth and mixing, and (iv) finding out the way of increasing the mixing efficiency.

2. GOVERNING EQUATIONS

The flow field is governed by the two-dimensional full Navier-Stokes equations with conservation equations of species. Body forces are neglected. For non-reacting flow, these equations can be expressed by

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

Where

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

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

The following terms are expressed as

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

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

$$\tau_{xy} = \tau_{yx} = \mu(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})$$

$$q_x = -k\frac{\partial T}{\partial x} - \sum_{i=1}^{ns} D_{iml} h_i \frac{\partial Y_i}{\partial x}$$

$$q_y = -k\frac{\partial T}{\partial y} - \sum_{i=1}^{ns} D_{iml} h_i \frac{\partial Y_i}{\partial y}$$

$$\dot{m}_x = -\rho D_{iml} \frac{\partial Y_i}{\partial x}$$

$$m_y = -\rho D_{iml} \frac{\partial Y_i}{\partial y}$$

$$\lambda = \frac{2}{3}\mu$$

3. RESULTS AND DISCUSSION

3.1 Physics of Fluid dynamics

Figure 2 shows the velocity vectors with streamlines just behind the finite base for case 1~5. In Fig.2(a) the upper recirculation rotates clockwise while the lower recirculation rotates counterclockwise. The flows expand and high interaction occurs after recirculation. The recirculation zones spread downstream, increasing its length in longitudinal direction. The stream lines indicate that both of the recirculations are created by the hydrogen flow. For other cases in Figs.2 (b) to (e), after entering into the first recirculation, portion of the hydrogen flow can not complete the recirculation. This portion of hydrogen makes intimate contact with air and deflects 180° due to the high momentum of air stream. The velocity in recirculation is low and therefore hydrogen has much time to contact with air resulting in high diffusion. Throughout the study, the momentum of air is higher than that of hydrogen, due to which the expansion of hydrogen is high behind the base while the expansion of the air stream is low. Due to expansion and interaction between two streams hydrogen enters in the recirculation region and mixes with air by diffusion and convection. By means of this, recirculation plays a vital role to enhance mixing.

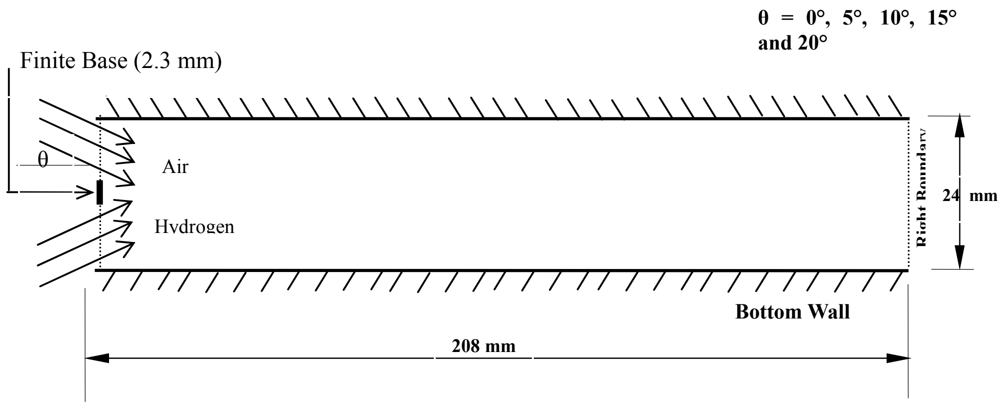

Fig 1.Schematic diagram of calculation domain

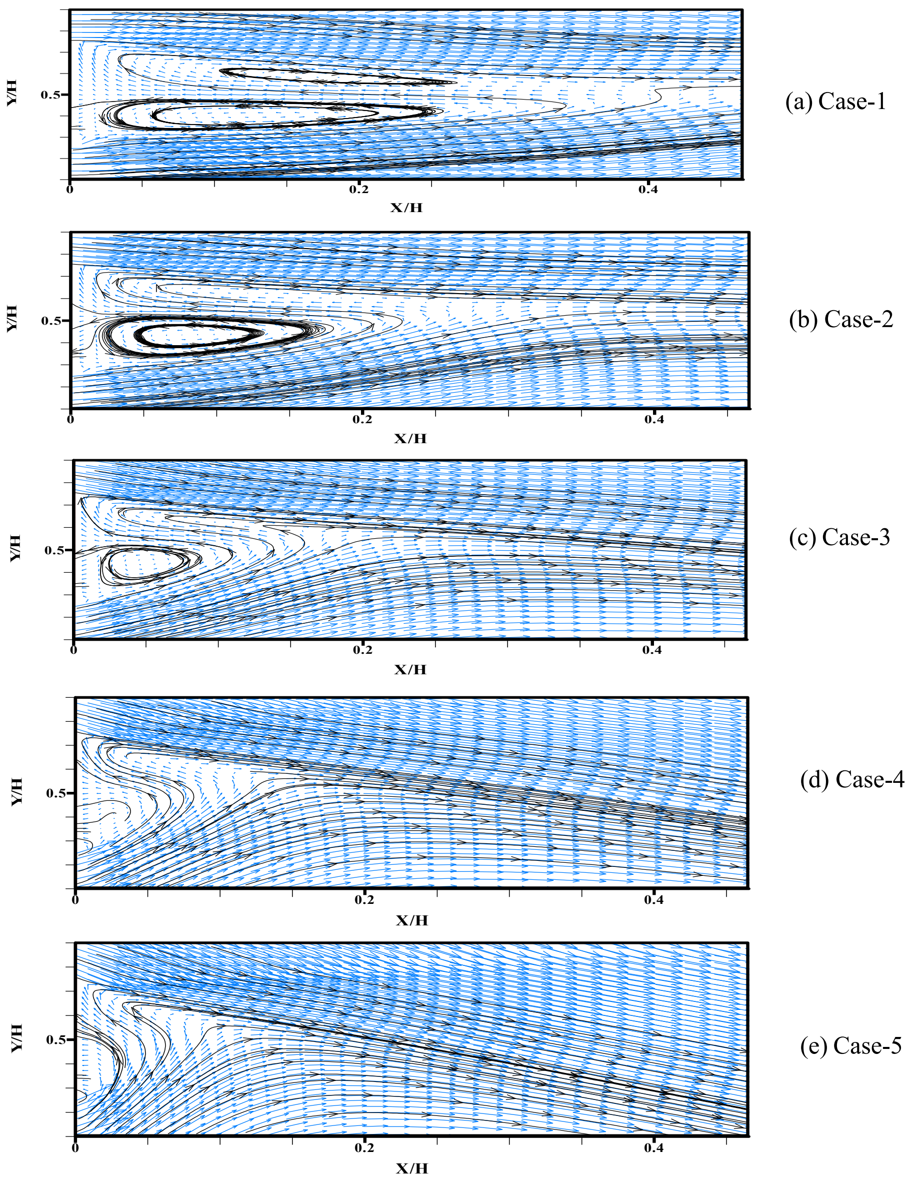

Fig 2. Vector and streamline representation of near flow circulating region for Case -1~5

Figure 2(b) shows the shear layer mixing regions spread with longitudinal distance until impingement occurs at approximately X/H = 0.22, which is shorter than case 1. Therefore, the area of recirculation zones in case-2 are smaller than case-1. Figures 2 (a~e) shows that with the increment of merging angle the size of both recirculations diminishes but more hydrogen molecules are entering in the recirculation region due to strong interactions and eventually more molecular and convection diffusion occurs. Another observation is that in Fig. 2(a) two recirculations are very clear but in Fig. 2(b) the upper recirculation vanishes and the size of lower recirculation decreases. Moreover, the streamlines generated from the same location of Fig. 2(a) and (b) indicate that more hydrogen molecules enter into the upper side of the recirculation region and make intimate contact with the air stream for case 2 than that of case 1.

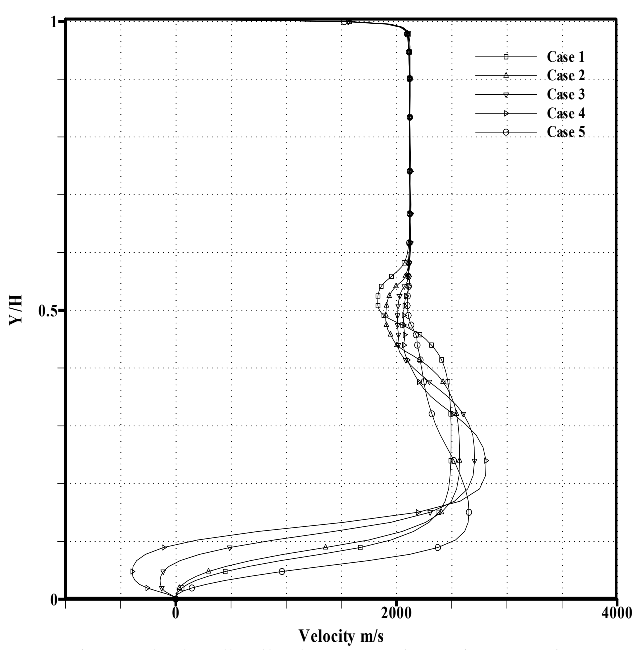

Fig.3 Velocity distribution at section X/H=5.98 for Case 1 to Case 5

Velocity distribution curves in Fig.3 show that velocities of the upper section are similar to all merging angles at constant pressure ratio. But the velocity of the lower part (hydrogen) increases at the downstream. The maximum velocity occurs at merging angle of 5.0º.

3.2 Structure of Shear Layers

The mole fraction contours give a structure of free shear layers created by the mixing of the two streams. Figure 4 shows the mole fraction contours of hydrogen. The mole fraction of hydrogen close to bottom wall is 0.95 and the contour line varies form 0.95 to 0.05 towards the upper wall. The increment of mole fraction between two adjacent contour lines is 0.05. As stated earlier, a thin base is located from Y/H = 0.45 to 0.55 in the middle of the two streams. Throughout the study hydrogen has less momentum than that of the air stream and eventually hydrogen will occupy more space after the thin base. For case 1 there is no initial deflection of shear layer due to identical pressure. But for cases 2~5 the shear layer deflects towards the bottom wall due to non-parallel mixing and higher density of air. The deflection angle is measured with respect to X-direction. The deflection angles for case 2, 3, 4 and 5 are 5.0º, 8.0º, 10.0º and 18.0º, respectively. The spreading of free shear layers also increases with the increment of merging angle. Further deflections of shear layer at downstream are fairly understandable for higher merging angles. The spreading of free shear layers is the highest for case 5 and case 1 it is the lowest. For all cases, the spreading of hydrogen increases as mixing angle increases. After this initial deflection all the shear layers deflect towards the upper boundary. In order to investigate how the details of the structure are affected by the mixing angles, the computational domain should be long enough to allow the shear layer to become unstable naturally. So it is found that the deflection angles as well as spreading of free shear layer increase with increases the merging angle.

3.3 Mixing Efficiency

Mixing efficiency has been calculated on the basis of flammability limits of hydrogen and air. So, in the calculation of mixing efficiency the region having the mole fraction range of hydrogen from 0.05 to 0.75 has been taken into consideration. The mixing of hydrogen in air can be occurred by means of (i) interaction between two streams, (ii) turbulence and convection due to recirculation and velocity of the flow, or (iii) molecular diffusion due to density gradient. The performance of different cases is evaluated by calculating the mixing efficiency. Figure 5 shows the mixing efficiency along the physical model for different cases. For all cases the mixing efficiency increases sharply just behind the base due to expansion at the thin base corner and recirculations. The sharp increment in efficiency is caused by the interaction of two streams. In downstream the mixing is very slow in shear-layer caused by weak molecular diffusion for supersonic nature of the flow. From Fig.5 it can be observed that the strong interaction of the two streams in case 5 causes high penetration of air in the hydrogen. Consequently, case 5 has the highest increment of mixing efficiency near the left boundary. Whereas at lower merging angle, weak interaction of two streams causes weak penetration and lower mixing efficiency. In Fig.5 at X/H= 2 the mixing efficiencies of the cases 1,2,3,4 and 5 are 4.9, 6.5, 11.5, 18.0 and 24.0%, respectively i.e. in upstream mixing efficiency increases as merging angle increases. In the downstream increase of mixing for case 1 is higher than that for case 2, whereas for case 3, 4 and 5 it remains almost constant. This increasing trend indicates that case 1 has the maximum hydrogen diffusion in the downstream. So, for the cases 3~5 the longer combustor might increase the cost of construction of combustor, provided that other parameters are identical. The overall mixing efficiency at outflow for cases 1, 2, 3, 4 and 5 are 7.5, 9.0, 13.5, 20.0 and 25.0%, respectively. So, overall mixing efficiency at the outflow boundary increases with the increase of merging angle.

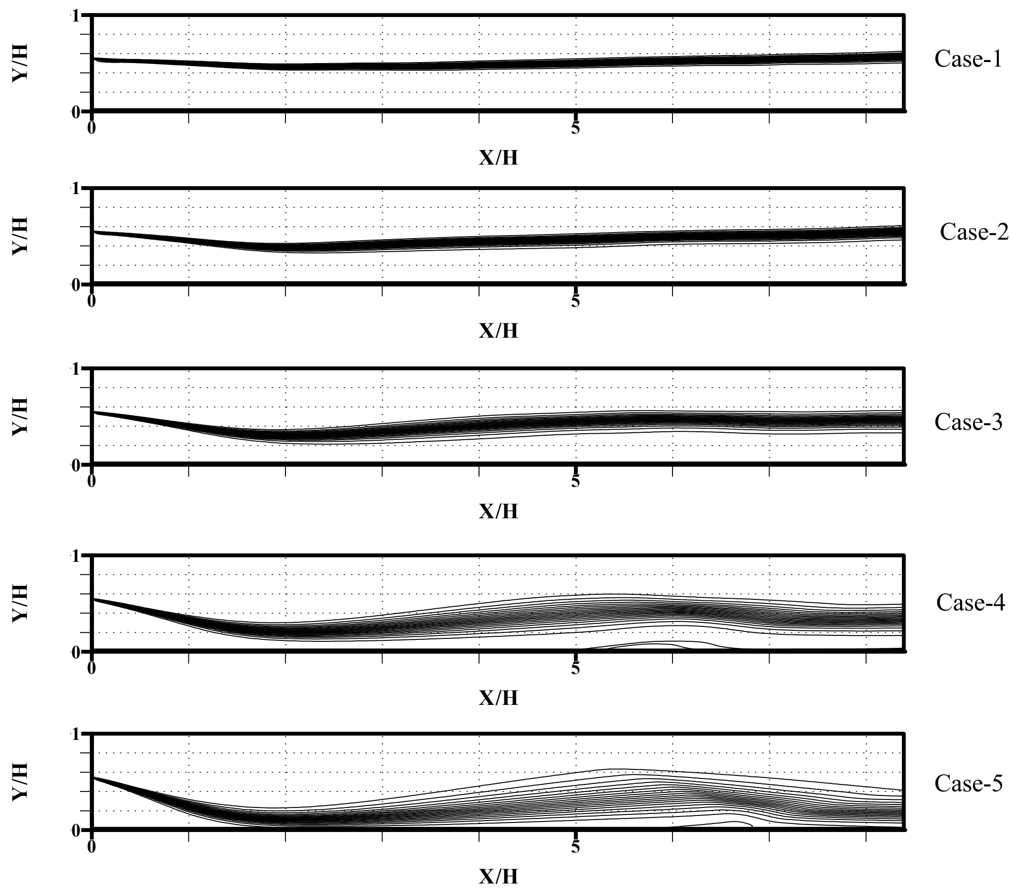

Fig 4.Mole fraction contour of hydrogen φ(0.05,0.95,0.05) for Case 1 ~ 5

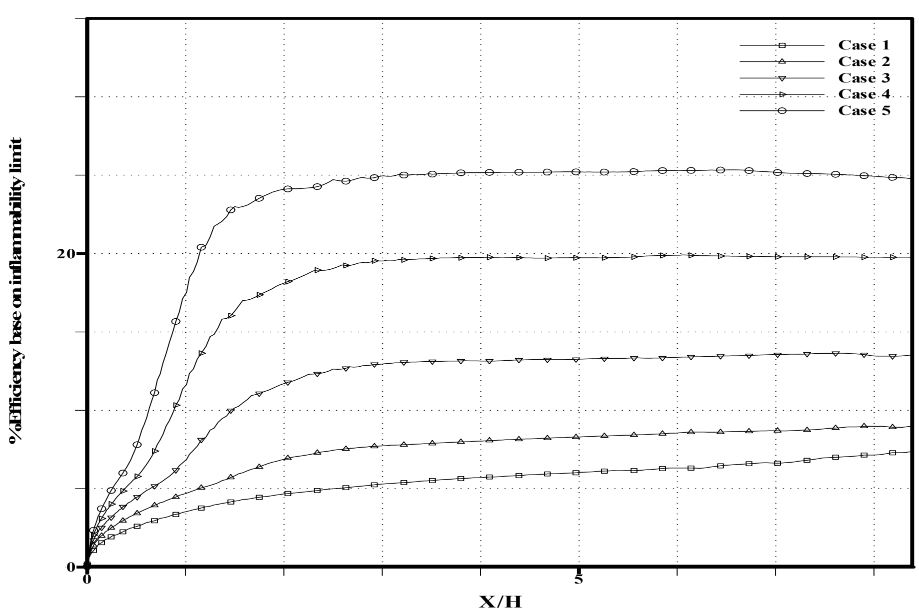

Fig 5. Mixing efficiency base on inflammability limit for Case 1 ~ 5

4. CONCLUSION

For good combustion in a supersonic combustor the need of efficient mixing is mandatory. Many experiments, theoretical and numerical studies have been performed on mixing, ignition and combustion in supersonic flow. In supersonic combustion, high penetration and mixing of fuel with oxidizer is difficult due to their short residence time in combustor. In the present study the effects of merging angle in a limited range of values on supersonic mixing have been studied and some information extract from this study. Due to finite base, hydrogen and air expand behind the base creating a separation region and a recirculation region. Both hydrogen and air streams move to each other and strike behind base. The velocity in recirculation is low and therefore hydrogen has much time to contact with air resulting in high diffusion. By varying merging angle it has been found that, interaction between the two streams increases with increase of merging angle but the area of recirculation increases. By the investigation of the recirculation region in detail, it has been found that although recirculation area decreases with the increase of merging angle, high amount of hydrogen enters into the recirculation region and eventually mixing efficiency increases. Due to high interaction of the streams high momentum exchange occurs and eventually high mixing occurs at upstream for high merging angle. At high merging angle shocks created in the flow-field are strong. Due to these strong shocks, pressure loss increases as the merging angle increases. Strong interactions and shocks in high merging angles reduce the pressure in outflow boundary.

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