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Computational analysis of supersonic combustion with swept ramp injection using K-ε turbulence model

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ABSTRACT
In this Paper numerical study with swept ramp injection in supersonic combustion of hydrogen has been presented. Coupled implicit scheme with finite rate chemistry model and K-ε Turbulence model have been used for modeling of supersonic combustion. The main issue in supersonic combustion is proper mixing within short burst of time. Because of the step on the top wall of the combustor, there exists an expansion fan generated just on the top wall at the entrance of the combustor, which is interacts with the oblique shock wave formed upstream of the combustor due to the shear layer deflecting into the core flow. The static pressures along the walls are normalized by the static pressure of the core flow. The present result is very promising and demonstrates that flamelet approach seems to be feasible to high-speed flows. The stagnation temperature in the combustion reaches up to 2830 k. Fluctuation in pressure and Mach number was due to shock train.

Introduction

Supersonic combustion is the key enabling technology for sustained hypersonic flights. In scramjet engines of current interest, the combustor length is typically of the order of 1 m, and the residence time of the mixture is of the order of Milliseconds. Due to the high supersonic flow speed in the combustion chamber, problems arise in the mixing of the reactants, flame anchoring and stability and completion of combustion within the limited combustor length. The flow field in the scramjet combustor is highly complex. It is shown that when the flight speed is low, the kinetic energy of the air is not enough to be used for the optimal compression. Further compression by machines is needed in order to obtain a higher efficiency. For example, a turbojet employs a turbine machine for further compression. When the flight speed is higher than a certain value, the air flow entering a combustor will remain to be supersonic after the optimal compression. With a further compression (i. e. deceleration), the efficiency of the engine will decrease. Therefore the combustion has to take place under the supersonic flow condition. This kind of air-breathing engine, which works under hypersonic flight condition, is called the supersonic combustion ramjet (Scramjet). The term of "supersonic combustion" applied here means the combustion in a supersonic flow. The efficiency of heat supply to the combustion chamber based on the analysis of literature data on combustion processes in a confined high-velocity and high-temperature flow for known initial parameters is considered. This was given by Mr.P.K.Tretyakov[1]. The process efficiency is characterized by the combustion completeness and total pressure losses. The main attention is paid to the local intensity of heat release, which determines, together with the duct geometry, techniques for flame initiation and stabilization, injection techniques and quality of mixing the fuel with oxidizer, the gas-dynamic flow regime. The study of supersonic combustion of hydrogen has been conducted by Shigeru Aso& Arifnur Hakim et al. [2] using a reflected-type shock tunnel which generated a stable supersonic ir flow of Mach number of 2 with the total temperature of 2800K and the total pressure of 0.35 MPa. He concluded that The Schlieren images show that the increase of injection pressure generated strong bow shock, resulting in the pressure loses.

Supersonic combustion data obtained at the low static temperatures appropriate for an efficient scramjet engine are reviewed by T.Cain and C. Walton [3]. Attention is focused at the methods by which the fuel was ignited and combustion maintained. This is particularly common for supersonic combustion experiments and many examples are found in the literature of experiments conducted with inlet temperatures much higher than practical in flight. There is a good reason for this: it is difficult to sustain a hydrogen or hydrocarbon flame in a low temperature supersonic flow. A well designed combustor makes this possible; a less effective combustor can be made to function simply by elevating the static temperature until spontaneous ignition is achieved. Low combustor entry temperature is desirable/essential due to intake and nozzle limitations.

This paper aims in particular at the application of scalar and joint scalar-velocity-turbulent frequency PDF (probability density functions) methods to supersonic combustion done by P. Gerlinger & H.Mobus et al [4]. Supersonic combustion has the potential of providing propulsion systems for a new generation of air breathing space transportation vehicles. Accuracy is an all-important issue. Supersonic combustion is commonly considered as one of the most demanding applications of current CFD tools.. However, rapid ignitions as well as fast and complete combustion are vital to reduce hardware length and weight. Therefore, hydrogen is the fuel of choice owing to its short ignition delay and, in view of structural mechanics, because of its efficiency in cooling. As a last point it may be concluded that more high-quality experimental data are indispensable for further evaluation of high speed combustion models.

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A numerical study of mixing and combustion enhancement has been performed by Peter Gerlinger&Peter Stoll et al[5] for a Mach 2 . Due to the extremely short residence time of the air in supersonic combustors, an efficient (rapid and with small losses in total pressure) fuel/air mixing is hard to achieve. K. Kumaran&V.Babu [6] investigates the effect of chemistry models on the predictions of supersonic combustion of hydrogen in a model combustor. The calculations show that multi step chemistry predicts higher and wider spread heat release than what is predicted by single step chemistry. In addition, it is also shown that multi step chemistry predicts intricate details of the combustion process such as the ignition distance and induction distance. a detailed chemistry model with 37 reactions and 9 species was used and the results from these calculations were compared with those obtained using single step chemistry.

However, the prediction of the myriad details of the heat release/ignition delay, which offer insights into the combustion process, demands a comprehensive chemistry model as demonstrated in this work.

A numerical study of atomization, i.e. breakup of a high speed jet and spray formation, is presented by Zhiliang Xuxk & Wohno Ohzk et al [7] using the Front Tracking method in 2D. The high speed flow in the nozzle gives rise to cavitation, i.e. a mixed liquid-vapor region.

A Lagrangian model of turbulent combustion in high speed flows has been used in conjunction with an efficient RANS–AMA strategy to simulate both non-reactive and reactive turbulent supersonic coflowing jets. Liquid hydrocarbon supersonic combustion has been experimentally investigated by C. GRUENIG & F. Mayinger [9] . Kerosene was burnt in a steady, vitiated Mach 2.15 - air flow of a model scramjet combustor. The fuel is injected into the supersonic air stream by means of pylons. By the addition of small amounts of hydrogen to the kerosene the liqid fuel jet is dispersed and a fine spray produced. However, this additional fuel jet dispersion is not necessary for the supersonic combustion if the fuel is injected normally into the cross flow. combustor ignition behaviour, the air stream temperature can be reduced below the combustor ignition level Tmin once the combustor has ignited. Below Tflame-out the time scale ratio tignition/tresidence reaches its unstable regime again and the flame extinguishes.

Kyung Moo Kim & Seung Wook Baek et al [10] describes the numerical investigations concerning the combustion enhancement when a cavity is used for the hydrogen fuel injection through a transverse slot nozzle into a supersonic hot air stream.

The combustor with cavity is found to enhance mixing and combustion while increasing the pressure loss, compared with the case without cavity. But it is noted that there exists an appropriate length of cavity regarding the combustion efficiency and total pressure loss.

Usually, the cavity was found to increase both the total pressure loss and the temperature of the combustor while enhancing the combustion of fuel and oxidizer. A large-eddy simulation (LES) model with a new localized dynamic sub grid closure for the magneto-hydrodynamics (MHD) equations is used to investigate plasma-assisted combustion in supersonic flow by Kenji Miki&Joey Schulz et al [11]. A 16- species and 74-reactions kinetics model is used to simulate hydrogen-air combustion and high-temperature air dissociation. It is observed that an electrical discharge creates a high temperature and a radical rich concentration region in the recirculation zone that aids in ignition and flame-holding. When an uniform magnetic field is applied, mixing is significantly enhanced since the shock structure ahead of the fuel jet is weakened and fuel penetration into the air cross flow is increased. P Manna&D Chakraborty[12] shows the Reacting./low field of H l-air combustion behind a backward fating step in a ,"constant area combustor is simulated numerically by solving three-dimensional Navier Stokes equations along with K-e turbulence model and fast rate chemistry. Investigation of kerosene combustion in a Mach 2.5 flow was carried out using a model supersonic combustor with cross-section area of 51 mm * 70 mm and different integrated fuel injector/flameholder cavity modules is done by G. Yu&J.G. Li et al[13]. Experiments with pure liquid atomization and with effervescent atomization were characterized and compared. Under the same operation conditions, comparison of the measured static pressure distributions along the combustor also shows that effervescent atomization generally leads to better combustion performance than the use of pure liquid atomization.

Mathematical Formulation

Physical model

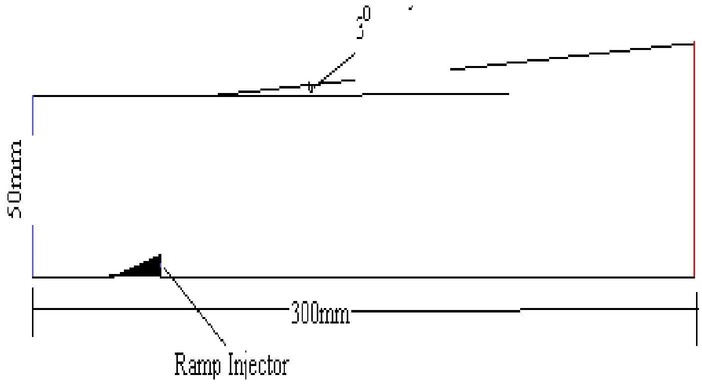

Figure 1 Physical model of Supersonic Combustor.

Governing Equations

The advantage of employing the complete Navier-Stokes equations extends not only o the investigations that can be carried out on a wide range of flight conditions and geometries, but also in the process the location of shock wave, as well as the physical characteristics of the shock layer, can be precisely determined.

We begin by describing the three-dimensional forms of the Navier-Stokes equations below. Note that the two-dimensional forms are just simplification of the governing equations in the three dimensions by the omission of the component variables in one of the co-ordinate directions.

Neglecting the presence of body forces and volumetric heating, the three-dimensional Navier-Stokes equations are derived as [34]

Continuity: $$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \qquad (1)$$

x-momentum: $$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho vu)}{\partial y} + \frac{\partial(\rho wu)}{\partial z} = \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \qquad (2)$$

y-momentum: $$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho vv)}{\partial y} + \frac{\partial(\rho wv)}{\partial z} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} \qquad (3)$$

z-momentum: $$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho ww)}{\partial z} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_{zz}}{\partial z} \qquad (4)$$

energy:
$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial(\rho uE)}{\partial x}+\frac{\partial(\rho vE)}{\partial y}+\frac{\partial(\rho wE)}{\partial z}=\frac{\partial(u\sigma_{xx}+v\tau_{xy}+w\tau_{xz})}{\partial x}+\frac{\partial(u\tau_{yx}+v\sigma_{yy}+w\tau_{yz})}{\partial y}+\frac{\partial(u\tau_{zx}+v\tau_{zy}+w\sigma_{zz})}{\partial z}+\frac{\partial(k\frac{\partial T}{\partial x})}{\partial x}+\frac{\partial(k\frac{\partial T}{\partial y})}{\partial y}+\frac{\partial(k\frac{\partial T}{\partial z})}{\partial z} \quad (5)$$

Assuming a Newtonian fluid, the normal stress σxx, σyy, and σzz can be taken as combination of the pressure p and the normal viscous stress components τxx, τyy, and τzz while the remaining components are the tangential viscous stress components whereby τxy= τyx, τxz= τzx, and τyz= τzy. For the energy conservation for supersonic flows, the specific energy E is solved instead of the usual thermal energy H applied in sub-sonic flow problems. In three dimensions, the specific energy E is repeated below for convenience:

$$E = e + \frac{1}{2}(u2 + v2 + w2) \quad (6)$$

It is evident from above that the kinetic energy term contributes greatly to the conservation of energy because of the high velocities that can be attained for flows, where Ma>1. Equations (1)-(6) represent the form of governing equations that are adopted for compressible flows.

The solution to the above governing equations nonetheless requires additional equations to close the system. First, the equation of state on the assumption of a perfect gas in employed, that is,

P=ρRT,

Where R is the gas constant.

Second, assuming that the air is calorically perfect, the following relation holds for the internal energy:

e= C_v T,

Where C_v is the specific heat of constant volume. Third, if the Prandtl number is assumed constant (approximately 0.71 for calorically perfect air), the thermal conductivity can be evaluated by the following:

$$k=\frac{\mu C_p}{Pr}$$

The Sutherland's law is typically used to evaluate viscosity μ, which is provided by

$$\mu=\mu_0\left(\frac{T}{T_0}\right)^{1.5}\frac{T_0+120}{T+120} \quad (7)$$

Where μ_0 and T_0 are reference values at standard sea level conditions.

Generalized form of Turbulence Equations is as follows:

$$(k)\ \frac{\partial k}{\partial t}+\frac{\partial(uk)}{\partial x}+\frac{\partial(vk)}{\partial y}+\frac{\partial(wk)}{\partial z}=\frac{\partial\left[\frac{V_T}{\sigma_k}\frac{\partial k}{\partial x}\right]}{\partial x}+\frac{\partial\left[\frac{V_T}{\sigma_k}\frac{\partial k}{\partial y}\right]}{\partial y}+\frac{\partial\left[\frac{V_T}{\sigma_k}\frac{\partial k}{\partial z}\right]}{\partial z}+(S_k=P-D)$$

$$(\epsilon)\ \frac{\partial \epsilon}{\partial t}+\frac{\partial(u\epsilon)}{\partial x}+\frac{\partial(v\epsilon)}{\partial y}+\frac{\partial(w\epsilon)}{\partial z}=\frac{\partial\left[\frac{V_T}{\sigma_k}\frac{\partial \epsilon}{\partial x}\right]}{\partial x}+\frac{\partial\left[\frac{V_T}{\sigma_k}\frac{\partial \epsilon}{\partial y}\right]}{\partial y}+\frac{\partial\left[\frac{V_T}{\sigma_k}\frac{\partial \epsilon}{\partial z}\right]}{\partial z}+\left(S_\epsilon=\frac{\epsilon}{k}(C_{\epsilon 1}P-C_{\epsilon 2}D)\right.$$

Where
$$P=2v_T\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right]+v_T\left[\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2+\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)^2\right]\ \text{and}\ D=\epsilon$$

Reaction Model

The instantaneous reaction model assumes that a single chemical reaction occurs and proceeds instantaneously to completion. The reaction used for the Scramjet was the hydrogen-water reaction:

$$2H_2 + O_2 \rightarrow 2H_2O. \quad (8)$$

The Equilibrium Model

The equilibrium model requires the specification of all the chemical species that might exist in the reacting mixture. No specific reactions need to be specified. This reaction model calculates the species concentrations at its equilibrium condition. The species specified for the reaction mixture were: H2, O2, N2, H2O, OH, O and NO.

The multi-step finite rate reaction model uses chemical rate equations to model any number reaction occurring in the system. The reaction rates are calculated using the Arrhenius equation:

$$k=A_pT^ne^{(-E_n/RT)} \quad (9)$$

Where: k is the reaction rate coefficient Ap is the pre-exponential constant Ea/R is the activation temperature n is the temperature exponent.

Computational Model Parameter

Geometry and grid arrangement

The initial design parameter for de Laval nozzle has taken at Mach 2 This was obtained by method of characteristics of nozzle program. The injector Diameter is 0.005m and the length of the combustor is 2m from throat and exit diameter is 0.2m

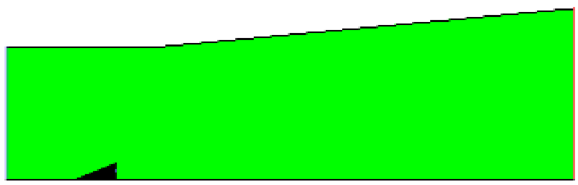

Figure 2 Supersonic Combustor at Mach 2

Result and Discussion

Numerical Simulation is presented here to understand the mixing and combustion behavior for Non-reacting and reacting flow, since in this model hydrogen is used as fuel and which product is water. Here to simulate the combustion model to see which turbulent model produces less OH at same condition. In this analysis flow with and without combustion with K-ε turbulent model has been investigated to see the combustion variation.

Non-reacting Flow

Figure 3 shows the path line on the symmetry plane colored by gradient of static pressure. The deflection of the path line and the pressure clearly shows the oblique shock from the corner edge of geometry and as well as expansion fan. This figure clearly shows the expansion fan around the corner edge arising upward deflection. There is a recompression shock just downstream due to shear layer formation. Figure 4 shows density contour where path line deflected due shock waves. The

Mach number field shows in figure 5 that some spot localized within the local fuel rich zone. Static temperature contour in figure 6, there is no combustion because of conditions of cold flow, One can note also the presence of expansion waves followed by recompression shocks, which generated by the center-body profile and interaction between the main stream and fuel-jet. The expansion and shock waves travel downstream producing pressure fluctuation and the flow travel along the method of characteristics as shown in figure 3 and 4. The deflection of path line and the accompanying density increases/decreases near the rich fuel zone.

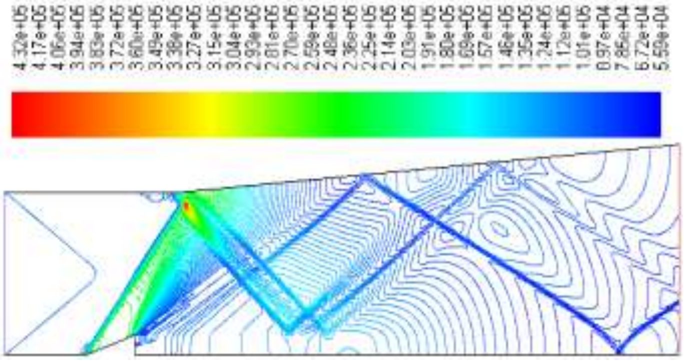

Figure 3. Contour of static Pressure

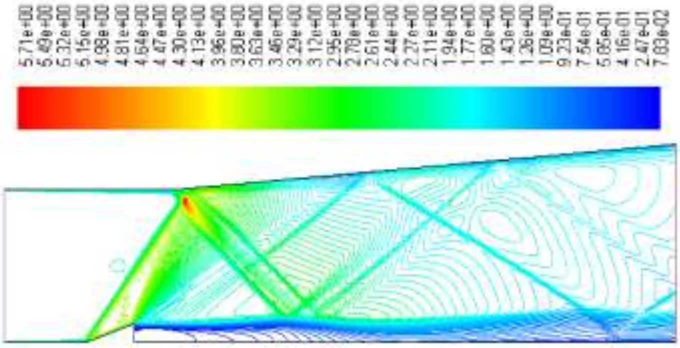

Figure 4. Contour of density

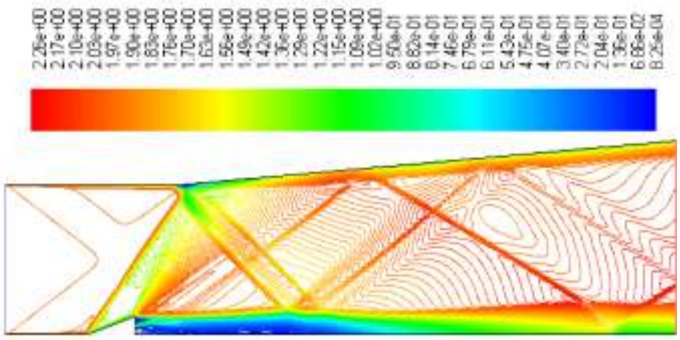

Figure 5. Contour of Mach number

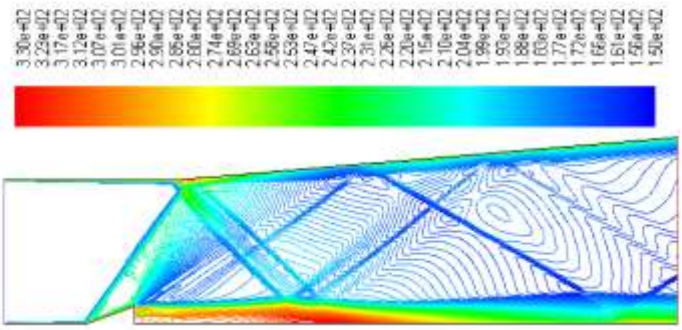

Figure 6. Contour of Temperature contour

Reacting Flow

Path lines on the plane colored by gradient of static pressure are shown in figure 7. Because of the step on the top wall of the combustor, there exists an expansion fan generated just on the top wall at the entrance of the combustor, which is interacts with the oblique shock wave formed upstream of the combustor due to the shear layer deflecting into the core flow. In Fig.7 the static pressures along the walls are normalized by the static pressure of the core flow.

Figure 8 shows the density variation, Since the intensity of the shock wave is much stronger than that of the expansion wave, after the interaction of these two waves, a high pressure region is formed on the top wall of the combustor, which is just ahead of the divergent part of the combustor. The XY plot of pressure distribution at different X location is shown in figure 13. From the xy plot it is clear that the maximum pressure is at x=0.07 because of combustion takes place near the x location and the minimum pressure is at x=0.28 compare to x=0.25.

From figure 14 it is clearly visualized that velocity is higher at x=.28 while it is lower at x=0.07 which just mirror of static pressure plot. Figure 9 present contour of Mach number. The Mach number is maximum at entry level because of oblique shock waves.

The maximum temperature reaches up to 2.83e+03 k in figure10. From the xy plot of temperature contour in figure 15 the maximum temperature is near the bottom wall because of the hydrogen is injected from bottom wall.

Maximum Value of H2 mass fraction at exit in figure 11 is 0.2 In the Figure above the blue line there is mass fraction of air. Due to the extremely short residence time of the air in supersonic combustors, an efficient fuel/air mixing is hard to achieve. The calculations show that multi step chemistry predicts higher and wider spread heat release than what is predicted by single step chemistry.

Flame temperature approaches the stagnation temperature in the region of high static temperature and has maximum heat release at a certain static temperature. This is due to the increase of flow velocity and stretch rate based on the increase of static temperature.

From figure 11 the maximum mass fraction of hydrogen is 0.9 near the injector, while there is variation due to shock trained form inside the injector as it is shown in figure 8.Near the wall, flow of oxygen is almost uniform as it comes in the contact of hydrogen the high temperature resulted out and water vapor is form as shown in figure 10.

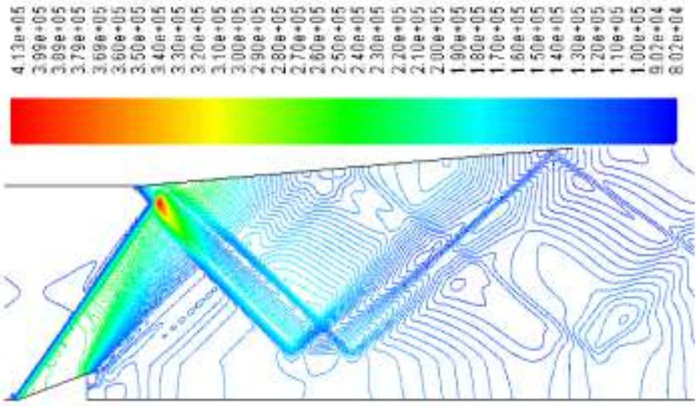

Figure 7. Contour of static pressure

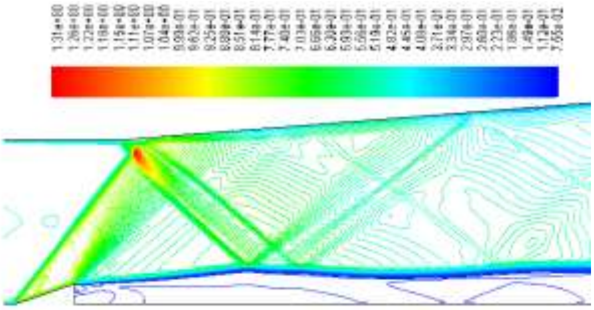

Figure 8. Contour of Density

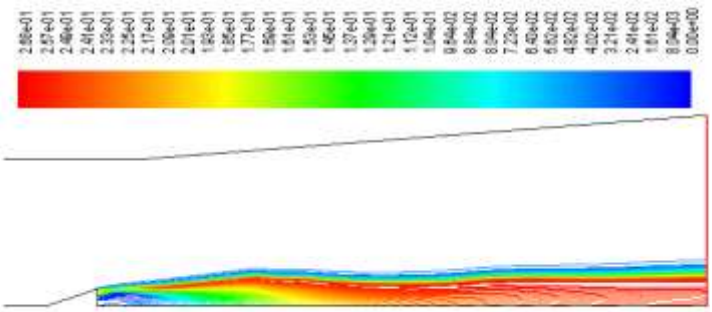

Figure 12. Mass fraction of water vapor

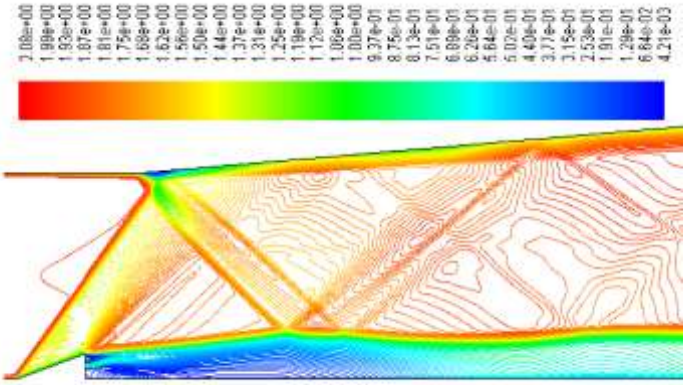

Figure 9. Contour of Mach number

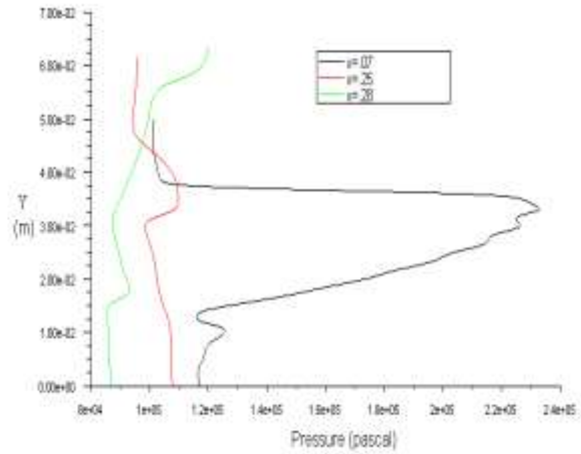

Figure13. xy plot of Pressure at different stream wise X-location

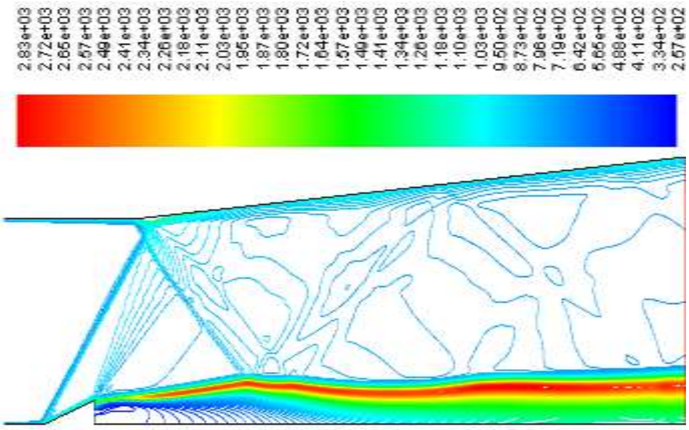

Figure 10. Contour of Temperature

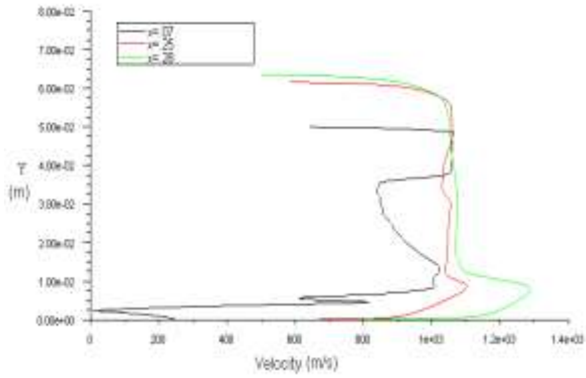

Figure 14. xy plot of Velocity at different stream wise X-location

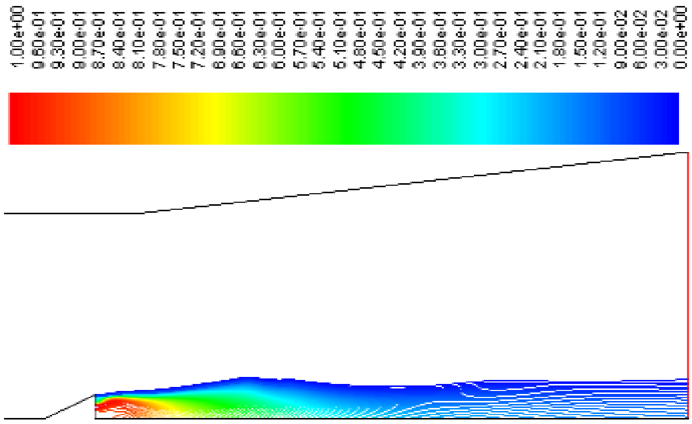

Figure 11. Mass fraction of hydrogen

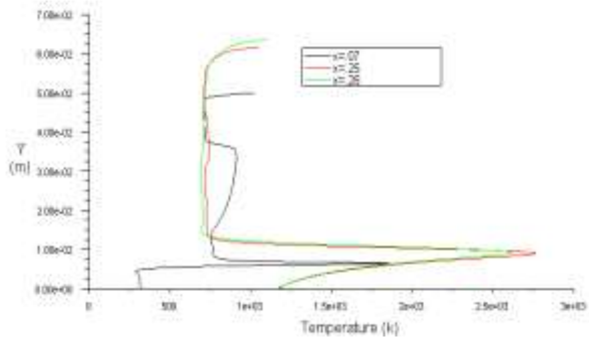

Figure 15. xy plot of Temperature distribution at different stream wise X-location

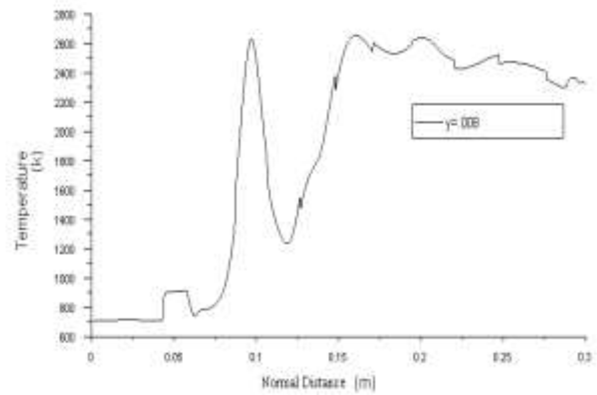

Figure 16. xy plot of Temperature distribution at Y=0.008

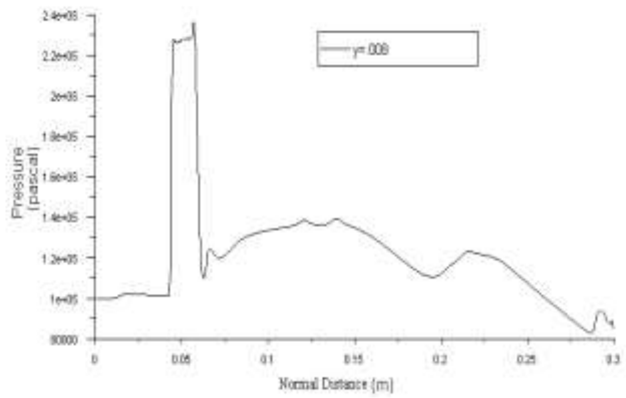

Figure17. xy plot of Pressure distribution at Y=0.008

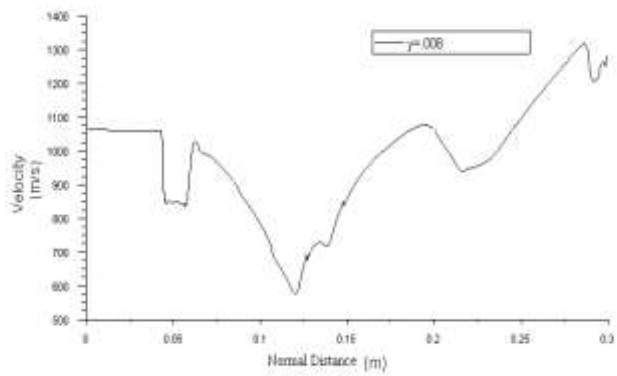

Figure18. xy plot of velocity distribution at Y=0.008

Conclusion

In this paper we dealt with supersonic combustion with swept ramp injection using finite rate chemistry model. The present result is very promising and demonstrates that flamelet approach seems to be feasible to high-speed flows. The current steady analysis validated the CFD solver for external supersonic combustion of H2/air. From the geometry results shows the better mixing in combustion chamber, caused by more extreme shear layers and stronger shocks are induced which leads loss in total pressure of the supersonic stream. The k-ε model is able to predict the fluctuation well in that region where the turbulence is reasonably isotropic.

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