Numerical Analysis of Supersonic Combustion by Strut Flat Duct Length with S-A Turbulence Model

K.M.Pandey and A.P. Singh

Abstract—**In this numerical study, supersonic combustion of hydrogen has been presented with strut flat duct length. The combustor has a single fuel injection parallel to the main flow from the base. Finite rate chemistry model with S-A Model have been used for modeling of supersonic combustion. In this paper strut at 60 with flat duct length analyzed for without hydrogen injection, with hydrogen injection and hydrogen injection with combustion. The investigation of the shock system produced by a strut injector with subsequent mixing, ignition and flame stabilization showed that the characteristics of the ignition process is considerably different from the shock induced ignition which has been postulated in the past. The ignition is achieved through the irreversible total pressure loss in the wake of Strut due to flat duct length. Flat duct lengths allow the ignition delay to occur before the pressure and temperature is decreased by the expansion. The presence of a boundary layer in the chamber changes the shock system and the ignition conditions in the chamber considerably.**

***Index Term*—supersonic combustion, S-A model, finite rate, stagnation temperature, flame speed, Mach number.**

I. 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 air 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.

II. MATERIAL AND METHODS MATHEMATICAL MODEL

A. Physical Model

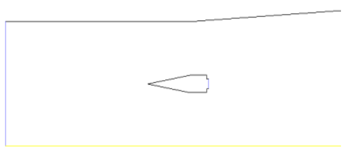

Figure 1 Physical model of strut with flat duct length Supersonic Combustor.

B. 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

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

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

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:

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

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

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 $\tau_{xy} = \tau_{yx}$, $\tau_{xz} = \tau_{zx}$, and $\tau_{yz} = \tau_{zy}$. 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:

$$E = e + \frac{1}{2}(u^2 + v^2 + w^2) \qquad (6)$$

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,

$$P = \rho RT,$$

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

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

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

C. 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:

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

III. Computational Model Parameter

A. Geometry and Grid Arrangement

The geometry 2d axi-symmetric computational domain was considered for the simulation of supersonic combustion , the initial design parameters for de Laval nozzle has taken at Mach 2 This was obtained by method of characteristics of nozzle program.

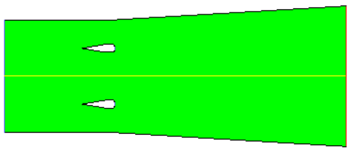

Figure 2 grid refinement of combustor

B. Numerical Methodology

The model supersonic combustor considered in the present work is show in figure 2. The combustor is 2.2 m long, and .06 m high at inlet and 0.2 m at exit. Vitiated air enter through the inlet with hydrogen being injected through at de-laval nozzle exit. The Mach number at inlet is two and stagnation temperature and pressure for Vitiated air are 1000K and 2.65 bar respectively. Fuel is injected from the base which located at nozzle exit. The inlet condition of the H_2 is considered as mass flow rate at 1 bar. In addition, 2ddp coupled with explicit model, turbulence and finite rate chemistry are also considered.

IV. Results and Discussion

Figure 3 shows the experimental and numerical shadow photograph as well as perspective view from the rear, in terms of velocity, H2 concentration, density, temperature and pressure. In the contour plot of the Mach number figure 3 the light shaded area indicates subsonic flow. In this the shear layers, originating at the upper and lower corners of the wedge, are much more pronounced in the combustion case because the combustion occurs within the shear layers between the hydrogen rich wake and free downstream air. The lower shock wave generates a strong pressure gradient in the hydrogen jet leading to a slight expansion of the jet. The contour of the jet, which can be represented by the Ma= 1 line, acts for the outer flow on the upper side of the jet as a compression ramp, resulting in the shock wave merging with the upper recompression shock at the upper wall. The flow can be roughly divided in to three regions: the introduction zone, where the turbulence determines the mixing and the mixing and the progress of combustion; a transitional zone that is dominated by large scale coherent flow structure, convective mixing, air entrainment and exothermicity, and highly turbulent combustion zone with large scale coherent structure and mixing. The large-scale structure originates in the shera layers that's roll-up, and become increasingly distorted with downstream due to vortex breakdown, occupying large part of the combustor due to dilatation resulting from exothermicity. The exothermicity leads to an overall increase in shear-layer thickness, which in turn, affect the subsequent reflection of the leading shock and the overall combustion chamber pressure. The large-scale structure causes momentum exchange by mixing high momentum air and low momentum hydrogen or product wake flow forcing from subsonic flow through supersonic free stream flow, together with exothermicity within thease structure.

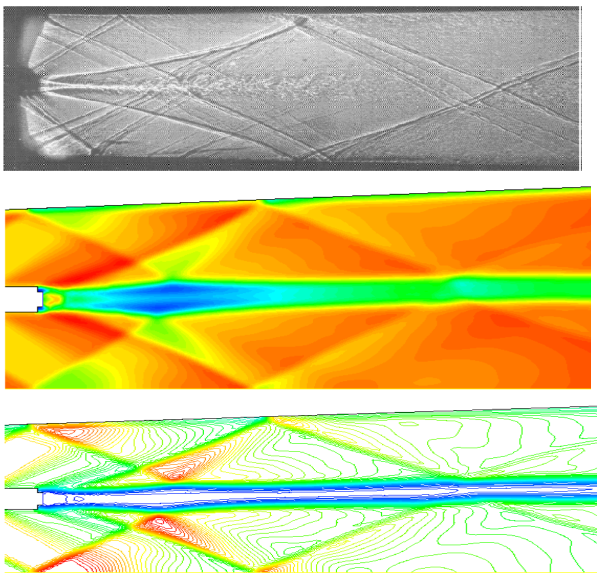

Figure 3. shadow Picture(top), Mach Number(middle) and density(bottom) Contour plot. The blue Shaded area indicates the region of subsonic flow.

Simulation of Flow in the Combustion Chamber:-

Two dimensional simulation of the flow in the chamber at (P0=7.8 bar, T0=612K, M=2) were analyzed chamber operation in order to see shock system and to obtain the zones with favorable condition for the self ignition. The contours of the density and static pressure are shown in the figure 4 and 5. The shock system produced by the strut increase the static temperature in the chamber. Without hydrogen injection strong expansion fans at the upper and lower corner of the wedge rapidly deflects the flow towards the center line here oblique shock waves show very good agreement with experimental data expansion fans. Near the base of the wedge associated with low base pressure and recompression shocks. After some distance the flow in the wake of the wedge accelerated back to the supersonic speed.

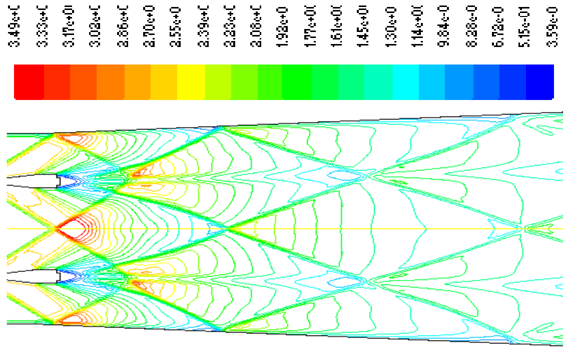

Figure 4. Contour of density without hydrogen injection.

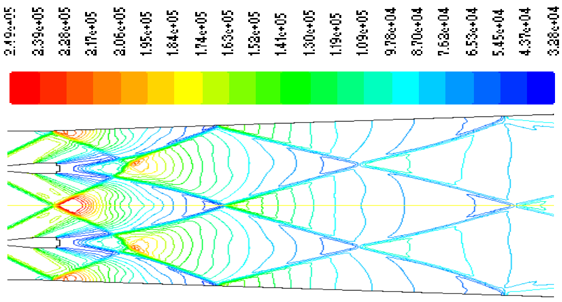

Figure 5. Contour of pressure without hydrogen injection.

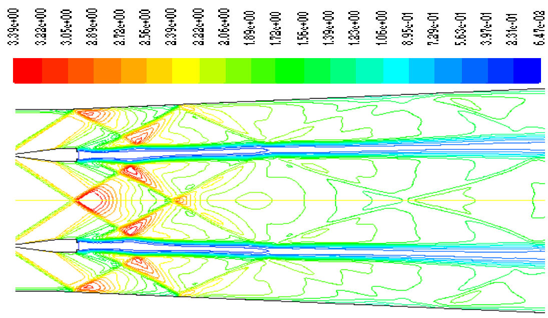

Figure 6. Contour of Density without combustion

A. *Injection without Combustion.*

In this present study injection of hydrogen without combustion is investigated. In figure 6 the flow from left to right, and the wedge , at the base of which hydrogen is injected in to the air steam is clearly visual. An oblique shock wave is formed on the tip of the wedge which reflect the upper and lower wall of the combustion chamber downstream of the recirculation bubble behind the wedge. This causes the characteristics shock pattern in the downstream region of the combustor. at the upper and lower walls the boundary layer is strongly affected by the reflection of this oblique shock wave. The boundary layer on the wedge surface separates at the base and shear layer is formed and naturally this is unstable. Before this process is completed, the reflection from the oblique shock at the tip of the wedge have started to interacted with shear layer

A detailed view inside the flow can be gaimned by comparing the experiment with computation Clearly seen are the overall complex flow structure with the leading shock waves generated at the tip of the wedge, the expansion fans at the base of the wedge followed by a recompression shock, and some shock reflections and deflections respectively. Figure 2 shows the pressure contours for the flat strut configurations at the plane of symmetry, the bottom wall, and a cross-sectional plane at the trailing edge of the strut. The oblique-shock systems created by these strut designs are highly three-dimensional flow structures. A bow-shock-type system can be observed in the cross-sectional plane (Figure 7).

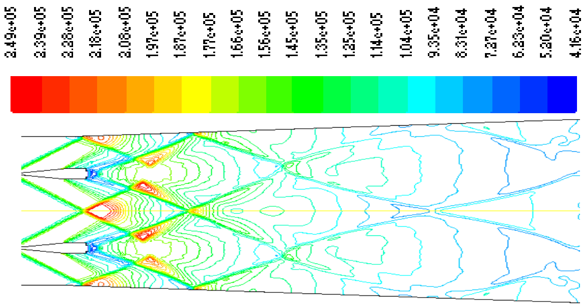

Figure 7. Contour of pressure without combustion.

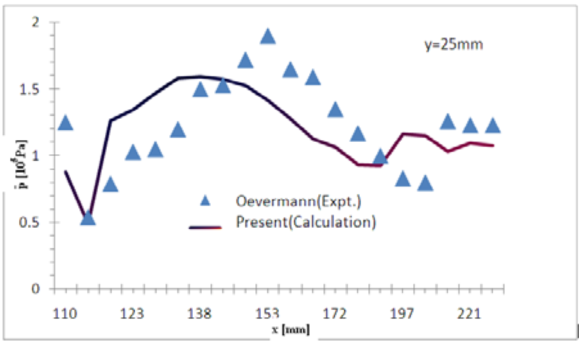

Figure 8 Pressure Distribution at middle of the channel at y=25mm

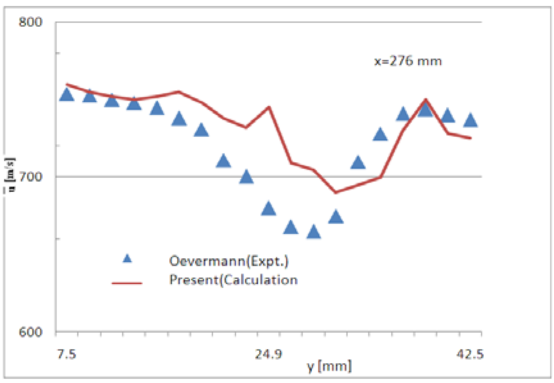

Figure 9 cross stream velocity profile at x=276

B. *Injection with Combustion*

The path line of the density contour and static pressure contour are presented here. As a result of pressure rise due to combustion, the expansion fan around the corner of the wedge that was seen previously, now it is totally absent. The region of subsonic flow is indicated in the pressure plot. From XY plot of static pressure for combustion chamber it is clearly visualized that after the hydrogen injection there is sudden increment in static pressure. Here hydrogen is injected through holes in the rear end of the wedge shaped flame holder, forming a combustible mixture, which is ignited, leading, in turn, to combustion of the hydrogen fuel. Comparison of this figure with figure 7 shows that the pressure rise due to combustion is not very high because in

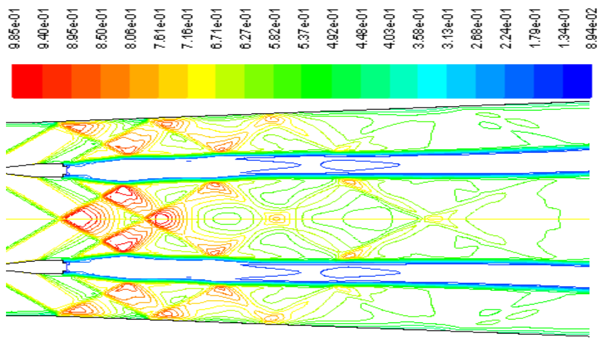

Figure 10. Contour of density with combustion.

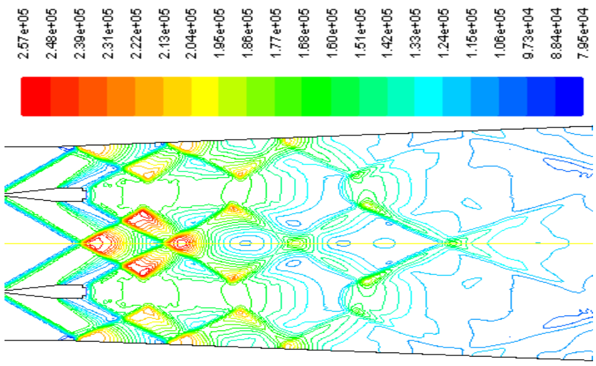

Figure 11. Contour of pressure with combustion.

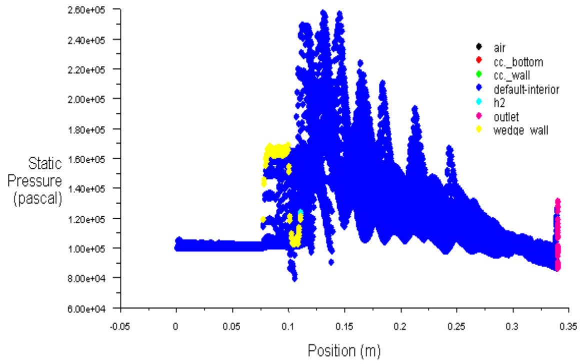

Figure 12. X Y Plot of pressure with combustion.

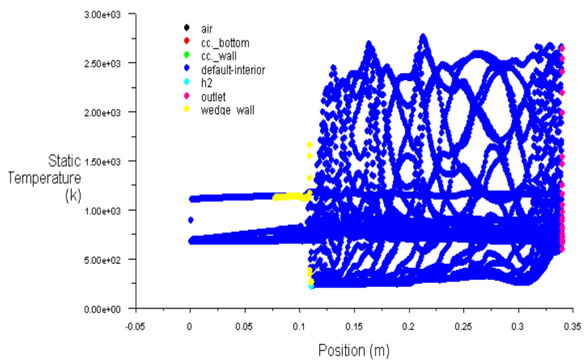

Figure 13. X Y Plot of Temperature with combustion.

this model equivalence ratio being quite low. Here in this figure Reflected shock wave from the bottom wall is stronger compare to that from the top wall. Actually the fuel is injecte in to tis subsonic zone, which helps in flame stabilization. From the XY plot of the static temperature after the injection of the hydrogen, the mixture is ignited and reaches up to 2700k as air in this model enters at 1200k. this computational result shows the fair agreement with Overmann report and also with experimental data[37].

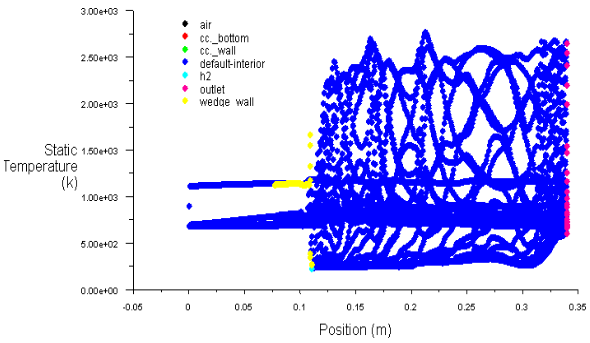

Figure 14. X Y Plot of Temperature with combustion

V. Conclusion

S-A Turbulent combustion model-flamelet model and finite rate reacting model are applied to simulate the supersonic combustor model. In this paper strut at 6^0 with flat duct length analyzed for without hydrogen injection, with hydrogen injection and hydrogen injection with combustion. The investigation of the shock system produced by a strut injector with subsequent mixing, ignition and flame stabilization showed that the characteristics of the ignition process is considerably different from the shock induced ignition which has been postulated in the past. The ignition is achieved through the irreversible total pressure loss in the wake of Strut due to flat duct length. Flat duct lengths allow the ignition delay to occur before the pressure and temperature is decreased by the expansion. The presence of a boundary layer in the chamber changes the shock system and the ignition conditions in the chamber considerably. When the combustion takes place in the entire chamber, an unstable shear layer is formed, before this process is completed, the reflection from the oblique shock at the tip of the wedge has started to interact with shear layer. To detailed study of species concentration also help in better understanding in present model.

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