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COMPUTATIONAL ANALYSIS OF SUPERSONIC COMBUSTION USING CAVITY BASED FUEL INJECTION WITH SPECIES TRANSPORT MODEL AT MACH NUMBER 4.17

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Abstract: This paper describes the numerical investigation of Supersonic combustion with Hydrogen as fuel injected with cavity of L/D ratio of 3 in two dimensional combustor at Mach number 4 using species transport model for combustion. In the present study the flow regime is simulated by using reailizable k-ε (two equations) model with standard wall function. The hydrogen fuel is injected just upstream of the cavity. A cavity flame holder is provided which injects hydrogen fuel in a supersonic hot air stream that facilitates enhanced mixing and combustion efficiency. The cavity is of interest because recirculation flow in cavity would provide a stable flame holding while enhancing the rate of mixing or combustion. 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.

Index Terms: Flameholder, k-ε model, Scramjet and Supersonic combustion.

1. Introduction

Supersonic combustion ramjet (SCRAMJET) engines which poses some major challenges that has attracted the attention and imagination of researchers worldwide. Ramjet also referred as “Flying Stovepipe” is an air breathing jet engine in which supersonic combustion take place & does not have rotating parts. The air enters the inlet & diffuser which is used for the compression of air Compression depends on velocity and increases strongly with vehicle speed. The same air enters to a combustion chamber which is mixed with injected fuel. This mixture is ignited and burns in the presence and aid of a flame holder that stabilizes the flame. In order to provide sustained combustion cavity flame holder is provided along the flow of combusting material, it was first proposed by the CIAM (Central Institution of Aviation Motors) in Moscow, was used for the first time in a joint Russian/French dual-mode scramjet flight-test. Due to the cavity the recirculation of the flow

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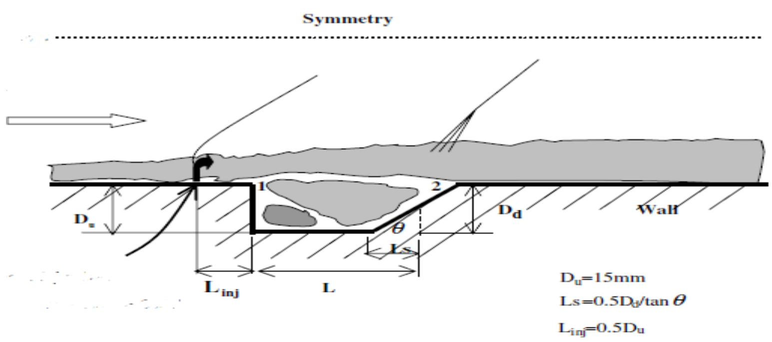
inside the cavity increases in order to get sustained combustion. In such combustors it gets a very short time for fuel injection, fuel-air mixing and subsequently combustion is available of the order of 1 ms and Hydrogen is used as a fuel in these engines. The complex phenomenon of Supersonic combustion involves turbulent mixing, shock interaction and heat release in Supersonic flow.

2. Literature Review

Kyung Moo Kim [1] worked on the topic “Numerical study on supersonic combustion with cavity-based fuel injection” their findings are cavity was found to increase both the total pressure loss and the temperature of the combustor while enhancing the combustion of fuel and oxidizer. By varying the aft wall angle, the offset ratio of upstream to downstream depth and the cavity length the following main results were found. A. Roux [2]. They have studied the instabilities of Ramjet through Large Eddy Simulation (LES) through LES codes developed by ONERA & CERFACS. With LES technique they have handled structured, unstructured & hybrid meshes. By Turbulence & Combustion models they have investigated ONERA Ramjet burner. They observed that although the two codes are very different numerically, both predictions are in good agreement with the experiment for the mean velocity field. The two LES produce different energy containing motions. With CEDRE, a low frequency dominates while AVBP produces different ranges of low frequencies that can be linked with acoustic modes of the configuration. O. Dessornes [3] ONERA and DLR joined together & made a dual mode Ramjet engine on this three experimental test were performed i.e. predictive, exploitation & computations. The different combustion regions are predicted i.e. sonic, transonic and supersonic is experimentally observed. Shock position could be piloted by adjusting the injection repartition & stabilization of a thermal throat near the chamber end has also been demonstrated. combustion chamber has two injection stages. The first is mainly dedicated to supersonic combustion whereas the second allows to have a subsonic combustion with a thermal throat located near the chamber end. The main experimental results are discussed and comparisons with 3D Naviers–Stokes computation are also presented. A. Roux [4] Compressible large eddy simulation on unstructured grids used to investigate non reacting and reacting flows in a simplified twin-inlet ramjet combustor was investigated. Reacting flow is compared to experimental results published by ONERA in terms of mean fields. This method shows that the most intense structure (at 3750 Hz) is the first transverse acoustic mode of the combustor chamber and the Rayleigh criterion obtained with POD illustrates how this transverse mode couples with unsteady combustion. Yuan shengxue [5] worked on the topic of “supersonic combustion”, and his findings are – The calculation of deflagration in supersonic flow shows that the entropy increment and the total pressure loss of the combustion products may decrease with the increase of combustion velocity. The oblique detonation wave angle may not be controlled by the wedge angle under weak under driven solution conditions and be determined only by combustion velocity. K. Kumaran and V. Babu [6] worked on the topic of “Investigation of the effect of chemistry models on the numerical predictions of the supersonic combustion of hydrogen”, and their findings are –Multi step chemistry predicts higher and wider spread heat release than what is predicted by single step chemistry. The single step chemistry model is capable of predicting the overall performance parameters with considerably less computational cost. J. P. Longwell [7] Different combustion problems in Ramjet are reported by considering Flame Stabilization, Stabilization by Baffles, Can Stabilizers and Flame Spreading & concluded empirical expression for reaction rate of fuel and air as a function of efficiency makes it possible to evaluate the possibilities for improvement of flame stabilizing and spreading devices by improved mixing performance increases. M.R. Gruber et al [8] cited that shear layer from the leading edge reattaches at the end of cavity trailing edge, thus generating an oblique shock. The high pressure and temperature region behind this shock can also act as an ignition source.

3. MATERIAL AND METHODS PHYSICAL MODEL

The Supersonic combustor geometry is attached with a cavity of l/d=3. This is 2 dimensional axisymmetric figure of the Supersonic combustor. The formulation for the cavity is given.



1: Leading edge of cavity 2: Trailing edge of cavity.

Θ: Aft angle D_u: Upstream depth

D_d: Downstream depth

Figure 1. Computational Geometry

4. Governing equations

The governing equation for the application of flight simulation comprise of mass conservation equation, the full Navier-Stokes equation, energy and species transport equations. Navier- Strokes equation helps in the investigation of flight simulation as well as shock wave. In our problem we are describing the three dimensional Navier-Strokes equation.

Continuity:

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

X momentum:

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho vu)}{\partial y}+\frac{\partial(\rho wu)}{\partial z}=\frac{\partial \sigma xx}{\partial x}+\frac{\partial \tau yx}{\partial y}+\frac{\partial \tau zx}{\partial z} \text{-------- (2)}$$

Y momentum:

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}+\frac{\partial(\rho wv)}{\partial z}=\frac{\partial \tau xy}{\partial x}+\frac{\partial \sigma yy}{\partial y}+\frac{\partial \tau zy}{\partial z} \text{------------------ (3)}$$

Z momentum:

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho ww)}{\partial z}=\frac{\partial \tau xz}{\partial x}+\frac{\partial \tau yz}{\partial y}+\frac{\partial \sigma zz}{\partial z}---------(4)$$

Energy:

$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial(\rho uE)}{\partial x}+\frac{\partial(\rho vE)}{\partial y}+\frac{\partial(\rho wE)}{\partial z}=\frac{\partial(u\sigma xx+v\tau xy++w\tau xz)}{\partial x}+\frac{\partial(u\tau yx+v\sigma yy+w\tau yz)}{\partial y}+$$

$$\frac{\partial(u\tau zx+v\tau zy+w\rho zz)}{\partial z}+\frac{\partial(K\frac{\partial T}{\partial X})}{\partial X}+\frac{\partial(K\frac{\partial T}{\partial Y})}{\partial Y}+\frac{\partial(K\frac{\partial T}{\partial Z})}{\partial Z}--(5)$$

4.1 Turbulence Model

Realisable k-ε model is used for the turbulence model. It has two equation model one for k and one for ε. We use k and ε to define velocity scale ϑ and length scale l.

$$\vartheta = K^{\frac{1}{2}} \text{---------(6)} \qquad l=\frac{K^{\frac{3}{2}}}{\varepsilon} \text{----------------(7)}$$

Eddy viscosity (μ_t) = $C\rho\vartheta l = \rho C_\mu \frac{K^2}{\varepsilon}$ -------------------(8)

The standard model uses the following transport equations used for K and ε.

$$\frac{\partial(\rho K)}{\partial t}+div(\rho K U)=div\left[\frac{\mu_t}{\sigma_k}gradk\right]+2\mu_t E_{ij}.E_{ij}-\rho\varepsilon \text{----------(9)}$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+div(\rho\varepsilon U)=div\left[\frac{\mu_t}{\sigma_\varepsilon}grad\,\varepsilon\right]+C_{l\varepsilon}\frac{\varepsilon}{K}2\mu_t E_{ij}.E_{ij}-C_{2\varepsilon\rho}\frac{\varepsilon^2}{K} \text{---------------(10)}$$

5. Computational and Model Parameters

Geometry and Mesh generation- Geometry is created in the Ansys14 workbench and the Mesh is generated in ICEM which is inbuilt facility of Ansys14, triangular mesh is used for the surface mesh.

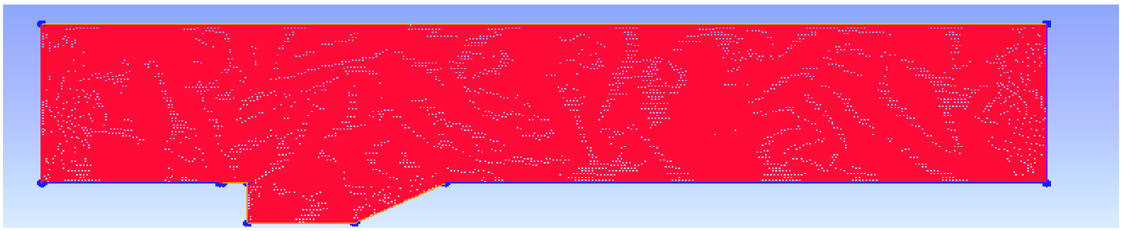


Figure2. Meshing

5.1 Boundary Condition

Before the simulation Grid independence test is carried out in order to check the quality of mesh and to get the optimised number of nodes and element of mesh beyond that no further variation in solution is found. For simulation air inlet and fuel inlet is considered as pressure inlet and outlet is considered as pressure outlet.

Input Parameters	**Air**	**Fuel**
Mach No	4	1
Temperature	1000K	600K
Pressure (atm)	1	7.57
Mass fraction of H2	0	1
Mass fraction of N2	0.767	0
Mass fraction of O2	0.213	0
Mass fraction of H2O	0.02	0
Turbulent Kinetic Energy(k)	10	2400
Turbulent Dissipation rate(ε)	650	10^8
Size of injector exit(d)	d = 1mm	

5.2 Computational Details

In the CFD modelling of the combustor we have used the Realisable k-ε turbulence model which is most suitable for the simulation of combustion regime. It is a two equation model that means it includes two extra transport equations to represent the turbulent properties of the flow. In order to achieve higher turbulence in combustion we have used the finite rate eddy dissipation model. The eddy dissipation is based on the hypothesis of infinitely fast reactions and the reaction rate is controlled by turbulent mixing. Air and fuel inlet is considered as pressure inlet and outlet is considered as pressure outlet and no-slip condition is applied for the walls. Energy equation is considered for considering the heat transfer phenomenon and monitor is placed and initialised from the air inlet. Ideal gas condition is considered for the combustion of hydrogen and air.

6. Result and Discussion

In Supersonic combustion very small amount of time of the order of millisecond is available which is very less for sustained combustion. In order to get better mixing and generation of better stabilised combustion cavity based fuel injection is provided to the combustor. It is also one of the major challenge that mixing of air and fuel at such a high velocity. Very short combustor residence time requires proper mixing of fuel and air. The various plots of properties such as Mach number, Static Temperature, Static pressure and mole fraction of Hydrogen and oxygen is shown. Plot of Static Pressure along the length of combustion chamber is also shown.

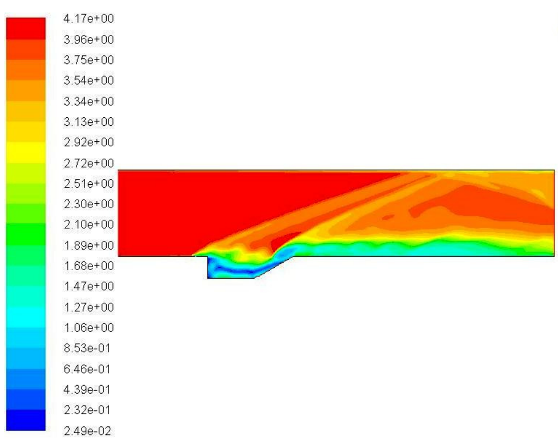


Figure 3. Contour of Mach number

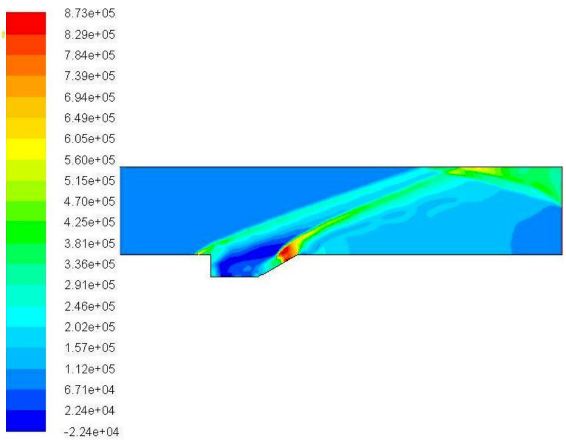


Figure 4. Contour of Static

Pressure

From Fig 5 it is evident that static temperature increases from inlet to the outlet. It is due to combustion of air and Hydrogen and the temperature increases from 601K to 3660K. Figure3 shows the contour of Mach number at 4.17 the deflection of path lines clearly shows the oblique shock wave from the upstream face of injection. Near the injector the flow is subsonic and due the cavity the flame is stabilised. The small instantaneous fluctuations of the bow shock are observed to average into a smoother and slightly thicker one. Figure shows the contour of static pressure which increases after the injection of fuel and attains a max value of 8733245 Pa and the minimum value of 67156 Pa. Figure 6 shows the plot of pressure variation along the length of the combustion chamber. Figure 7 and 8 shows the mole fraction of the hydrogen and oxygen in the combustion chamber.

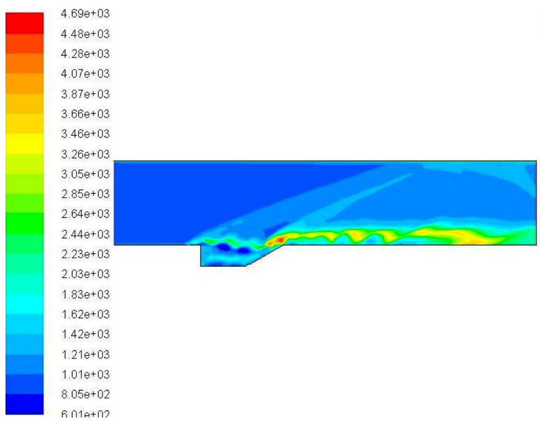


Figure 5. Contour of Temperature

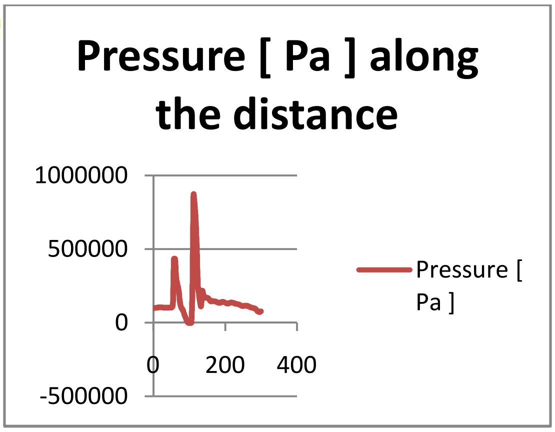


Figure 6. Plot of Static Pressure along the length

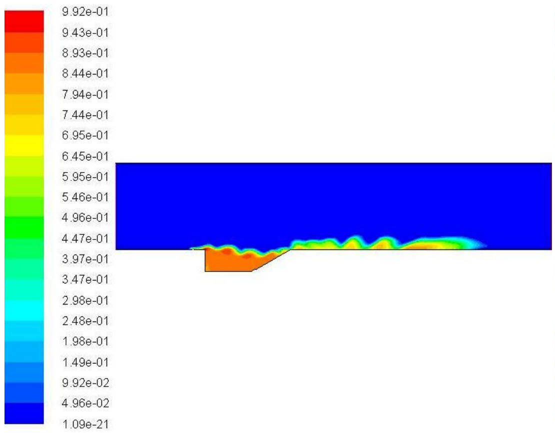


Figure 7. Mole fraction of H_2

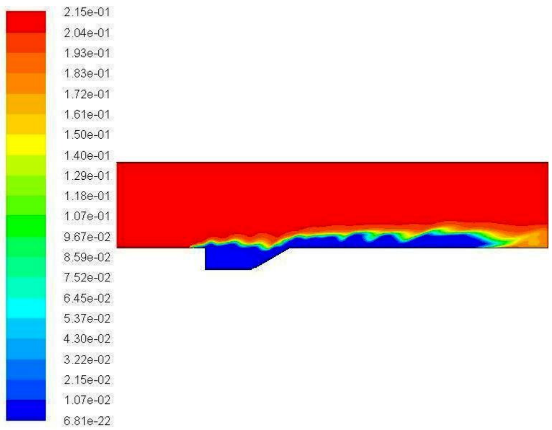


Figure 8. Mole fraction of O_2

7. Conclusion

CFD analyses of 2D cavity based fuel injection are carried out at Supersonic flow. The numerical simulation has been done with finite rate chemistry model using K-ε turbulence model utilizing CFD Fluent software. The kεTurbulence model also predicted the fluctuations in those regions where the turbulence is reasonably isotropic. By using cavity based fuel injection higher temperature and pressure can be attained in the chamber. From the maximum mass fraction of OH a very small amount of OH was observed after combustion. Combustor attains a very high temperature and pressure at outlet as compared to inlet. A Scramjet injector having a wall injector requires fuel inlet at high inlet pressure in order to attain combustion. Due to ever increasing human need for greater speed and reduced travel time, hypersonic combustion systems will become more and more important in the future.

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