

Computational Analysis of Hypersonic Combustion Using Flame Stabilizing Fuel Injection with Species Transport Model

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Abstract

This paper describes the numerical investigation of hypersonic combustion with Hydrogen as fuel injected with cavity of L/D ratio of 3 in two dimensional combustor using species transport model for combustion. The present study is based on the standard k-epsilon (two equations) model with standard wall functions. In the study fuel and air inlet are pressure based. In this model fuel is normally injected followed by cavity while the fuel is flowing upstream. For validating the model the k-ε results are compared with experimental results for static temperature along effective length. In the paper contour of static pressure, Mach number, static temperature, density and their respective plots are provided and problems regarding hypersonic combustion have been stated.

Keywords: Hypersonic combustion, k-ε, flame holding, injection.

1. Introduction

Supersonic combustion is one of the most promising technologies for air propulsion system. Ramjet (Scramjet) engine is used to achieve hypersonic propulsion i.e. Mach above 5. Lot of research is being carried out in the field of engine systems proposed for powering hypersonic vehicles, the scramjet (or supersonic combustion ramjet) appears to be the most promising therefore discussion in this paper will therefore centre on the scramjet engine. In the design of hypersonic combustion engine a problem of fuel injection and flame holding plays a very vital role in order to achieve performance, fuel and air must be mixed at molecular level. 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 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 hypersonic combustion involves turbulent mixing, shock interaction and heat release in hypersonic flow.

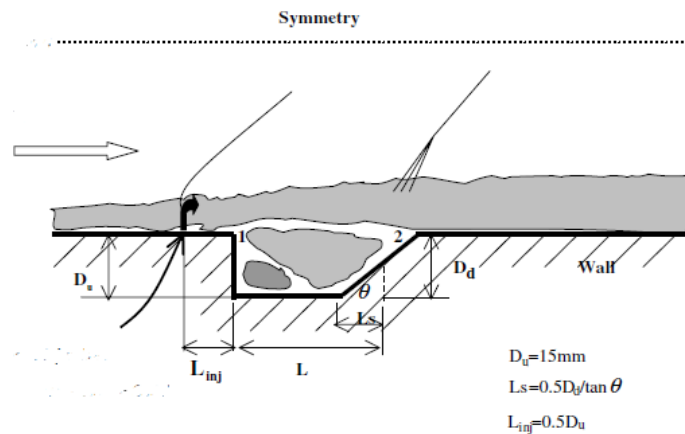
2. Literature Review

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. J. Sandeep [2] worked on “Investigation of supersonic combustion with cavity based injection in a scramjet combustor” their findings are aft ramp angle is decreased in cavity vorticity increased due to the trailing edge shocks, compared to $L / D=5$ cavity, vorticity is more in cavity with $L/D=3$, total pressure losses are more due to strong shock formed at transverse injection of fuel locations and shocks emanating at the cavity trailing edges. A.P. Singh [3] worked on “Numerical analysis of hypersonic combustion without cavity based injection with finite rate chemistry model” their findings are cavity was found to increase both the total pressure loss and the combustion and the temperature of the combustor while enhancing the combustion of the fuel oxidizer. Achieving efficient combustion is very much so dependent on producing homogeneous fuel/air mixture rapidly across the whole combustor. When the offset ratio of upper to downstream depth of the cavity increases, the combustion efficiency as well as the total pressure loss decreases. Gruber, M. R. [4] worked on the topic “Fundamental Studies of Cavity-Based Flame holder Concepts for Supersonic Combustors” finding are aft ramp angle plays an important role in determining the character of shear layer that spans the cavity. For a rectangular cavity $OR=1$ and $\theta=90^\circ$, a compression waves forms as the flow separates from the cavity’s upstream. A strong recompression occurs at the aft wall, and the flow is visibly unsteady. The pressure on the cavity fore wall decreases steadily and the recompression process occur more gradually with decreasing aft ramp angle. Higher drag coefficient and shorter residence times are found in cavities with shallower ramp angles. D. Cecere [5] worked on “Hydrogen/air supersonic combustion for future hypersonic vehicles” their findings are very complex structures due to the interaction between the four sonic H₂ cross flow injections and the airstream flowing at $M \approx 2.79$. A bow shock forms ahead of each H₂ injector: the interaction between bow shocks and boundary layers leads to separation zones where H₂ recirculates. In these recirculation zones, OH radicals are produced, indicating that a flame already starts upstream of the injectors and

downstream of the flow separation. LI Huifeng [6] worked on “Control-oriented Modelling for Air-breathing Hypersonic Vehicle Using Parameterized Configuration Approach” finding are the model can be applied to the investigation of control method for AHV during the cruise phase. The modelling process integrates several disciplines such as configuration design, aerodynamic calculation and scramjet modelling and control method. Therefore the modelling method makes it possible to conduct AHV aerodynamics/propulsion/control integration design. [7] In-Seuck Jeung worked on “Numerical Simulation of Supersonic Combustion for Hypersonic Propulsion” finding are Strong unsteady flow characteristics were identified for a scramjet combustor. The work appears to be the first of its kind, large flow disturbances can be generated by shear layer instability that may be triggered by the interactions with shock waves and instability caused by the cavity seems to override the shear layer instability caused by the shock-wave/shear-layer interactions when both instabilities are present. [8] Gianluca Iaccarino worked on “A QMU approach for characterizing the operability limits of air-breathing hypersonic vehicles” findings are uncertainty in both the inlet conditions and the calibration constants in the heat release model were evaluated to identify their impact on the unstart scenario. Finally the performance threshold corresponding to unstart triggered by thermal choking was identified and analyzed.

3. Material and Methods Physical Model

The hypersonic combustor geometry is attached with a cavity of $l/d=3$. This is 2 dimensional axisymmetric Fig. of the hypersonic 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

Fig. 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- Stokes equation helps in the investigation of flight simulation as well as shock wave. In our problem we are describing the three dimensional Navier-Stokes equation.

Continuity:

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

X momentum:

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

Y momentum:

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

Z momentum:

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

Energy:

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

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.

$$\vartheta = K^{\frac{1}{2}} \text{-----} \quad \text{(6)}$$

$$l = \frac{K^{\frac{3}{2}}}{\epsilon} \text{-----} \quad \text{-(7)}$$

$$\text{Eddy viscosity } (\mu_t) = C_\mu \rho \vartheta l = \rho C_\mu \frac{K^2}{\epsilon} \text{-----} \quad \text{-(8)}$$

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

$$\frac{\partial(\rho K)}{\partial t} + \text{div}(\rho K U) = \text{div} \left[\frac{\mu_t}{\sigma_k} \text{grad} k \right] + 2\mu_t E_{ij} \cdot E_{ij} - \rho \epsilon \text{-----} \quad \text{(9)}$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \text{div}(\rho \epsilon U) = \text{div} \left[\frac{\mu_t}{\sigma_\epsilon} \text{grad} \epsilon \right] + C_{1\epsilon} \frac{\epsilon}{K} 2\mu_t E_{ij} \cdot E_{ij} - C_{2\epsilon\rho} \frac{\epsilon^2}{K} \text{-(10)}$$

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.

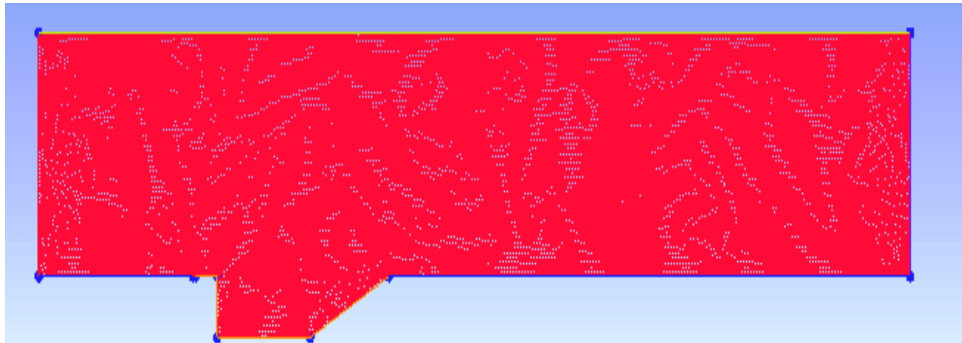


Fig. 2: Meshing.

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	5	1
Temperature	1000K	600K
Pressure (atm)	1	7.57
Mass fraction of H ₂	0	1
Mass fraction of N ₂	0.767	0
Mass fraction of O ₂	0.213	0
Mass fraction of H ₂ O	0.02	0
Turbulent Kinetic Energy(k)	10	2400
Turbulent Dissipation rate(ϵ)	650	108
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 hypersonic 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, Density, static pressure and turbulence kinetic energy is shown.

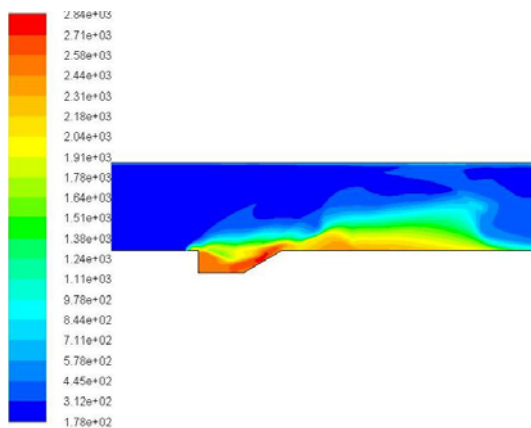


Fig. 3: Static Temperature

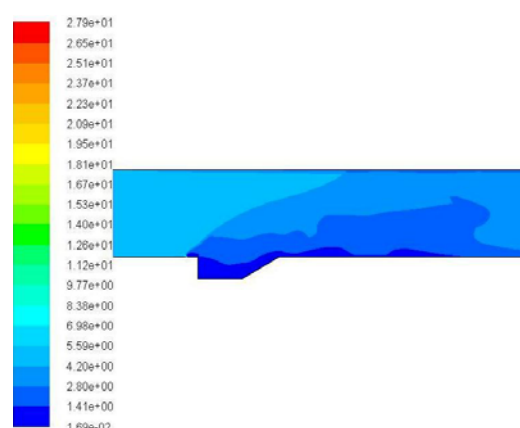


Fig. 4: Mach number.

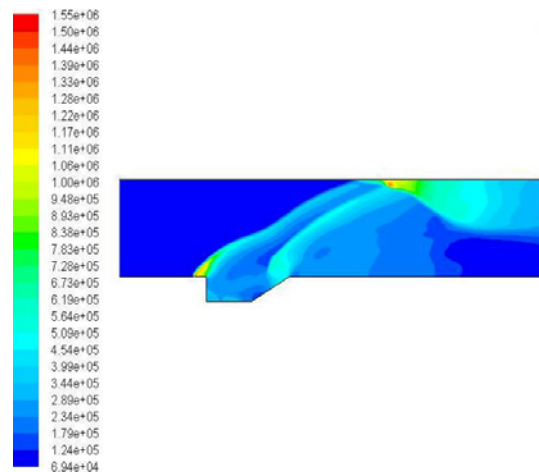


Fig. 5: Static Pressure,

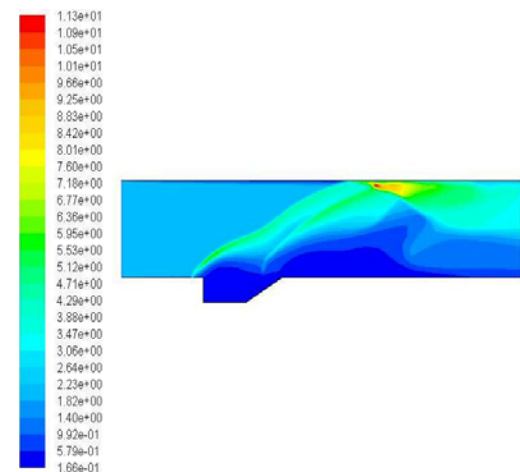


Fig. 6: Density.

From Fig 4 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 178K to 2840K. The contour of Density shows that the Density increases from the point of injection of Hydrogen and then it is subsequently decreases after mixing with air and combustion propagates. From the contour it is observed that the max value of density is 1.13023Kg/m^3 and the minimum value is $.166324\text{Kg/m}^3$. Figure4 shows the contour

of Mach number at 5.59. 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. Figure5 shows the contour of static pressure which increases after the injection of fuel and attains a max value of 1553245 Pa and the minimum value of 69456 Pa.

7. Conclusion

CFD analyses of 2D cavity based fuel injection are carried out at hypersonic flow. The numerical simulation has been done with finite rate chemistry model using K- ϵ turbulence model utilizing CFD Fluent software. The k ϵ Turbulence model also predicted the fluctuations in those regions where the turbulence is reasonably isotropic. 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.

References

- [1] Kyung Moo Kim, Seung Wook Baek (2004) "Numerical study on supersonic combustion with cavity-based fuel injection" *International Journal of Heat and Mass Transfer* 47 pp (271–286).
- [2] J. Sandeep, K. Bhardwajan (2012) "Investigation of Supersonic Combustion with Cavity based Injection in a Scramjet Combustor" *IJREAS* Volume 2, Issue 2 (February 2012) ISSN: 2249-3905.
- [3] A.P. Singh, K.M.Pandey (2013) *International Journal of Advanced Trends in Computer Science and Engineering*, Vol.2 , No.1, Pages : 60-66.
- [4] M. R. Gruber, R. A. Baurle, T. Mathur, and K.-Y. Hsu. (2001) "Fundamental Studies of Cavity-Based Flame holder Concepts for Supersonic Combustors", *Journal of Propulsion and Power*, Vol. 17, No. 1 , pp. 146-153.
- [5] D. Cecere, (2011) "Hydrogen/air supersonic combustion for future hypersonic vehicles" *international journal of hydrogen energy* 36.
- [6] LI Huifeng (2011) "Control-oriented Modelling for Air-breathing Hypersonic Vehicle Using Parameterized Configuration Approach" *Chinese Journal of Aeronautics* 24 page (81-89).
- [7] In-Seuck Jeung (2005) "Numerical Simulation of Supersonic Combustion for Hypersonic Propulsion" 5th Asia-Pacific Conference on Combustion, The University of Adelaide, Adelaide, Australia 18-20 July.

- [8] Gianluca Iaccarino (2011) “A QMU approach for characterizing the operability limits of air-breathing hypersonic vehicles” *Reliability Engineering and System Safety* 96 (2011) 1150–1160.
- [9] K.M.Pandey and T.Sivasakthivel (2011) “CFD Analysis of a Hydrogen Fueled Mixture in Scramjet Combustor with a Strut Injector by Using Fluent Software” *IACSIT International Journal of Engineering and Technology*, Vol.3, No.2, April.
- [10] J.P.Kalita, K.M.Pandey (2012) “Computational Analysis of Combustion Chamber Using Cavity-based fuel Injector with Non-Premixed Combustion Model” *Global Journal of Researches in Engineering Mechanical and Mechanics Engineering* Volume 12 Issue 3 Version 1.0.