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Numerical Analysis of Hydrogen-Fueled Scramjet Performance with Passive Techniques

Obula Reddy Kummitha[a*], K.M.Pandey[b], Rajat Gupta[c]
[a]*Mechanical Engineering, BVRIT, Narsapur - 502313, Telangana, India*
[b]*Mechanical Engineering, NIT Silchar, Silchar - 788010, Assam, India*
[c]*Mechanical Engineering, NIT Silchar, Silchar - 788010, Assam, India*

*Corresponding author Email: obulareddy.bec10@gmail.com

Performance of a scramjet engine mainly depends on two parameters which are defined as mixing efficiency and combustion efficiency. Combustion efficiency is greatly affected by the mixing efficiency, hence the major parameter to optimize the performance of scramjet combustor is the mixing efficiency of fuel and supersonic air. In this research paper, an attempt has been made to enhance the mixing efficiency of fuel and supersonic air by using passive techniques. The passive techniques are implemented to DLR scramjet by creating the wall attached fuel injectors at various locations and developed different computational geometries. Computational fluid dynamics tool ANSYS-FLUENT 15.0 has been used to solve the fluid flow governing equations and global one step reaction mechanism of fuel and air along with finite rate/eddy dissipation reaction model. Shear stress transport k-ω turbulence model is used for turbulence modeling. Validation of results has been performed with the DLR experimental results available in the open literature and found a good agreement between numerical and experimental results. From the analysis of numerical results, it has been observed that more recirculation regions, oblique and expansion shock waves are developed with the wall attached fuel injectors along with strut injector. These are helpful to penetrate into fuel stream and increasing the fuel carrying capacity, which can increase the mixing of fuel and supersonic air.

***Keywords*:** Scramjet, Strut, Mixing efficiency, combustion efficiency.

1. Introduction

Scramjet technology is the most interesting and ongoing research in aerospace technology. A scramjet is the advanced version of ramjet engine with supersonic combustion. The working of scramjet and its performance greatly depends on the individual performance of its components. Basically, the scramjet engine consists of three components which are defined as the inlet section, combustor, and diffusion section. All three components play a major role in the overall performance of the scramjet engine. Worldwide a great research is going on in scramjet technology by evaluating the performance of its individual components. The combustor is the major part to be considered as a research component due to its complex combustion process. In scramjet engine, the presence of air in the combustion chamber is around a tenth of milliseconds and it is not sufficient for ignition of fuel and supersonic air. Combustion process strongly depends on the mixing of fuel and air. Mixing of fuel and air at supersonic speed is a great challenging task.

Raul R et al.[1] performed an experimental and numerical investigation on mixing enhancement of fuel and supersonic air in scramjet combustor with turbulent Navier-Stokes fluid flow governing equations. In this study, a sinusoidal shape was considered and attached to the walls of scramjet combustor to make a configuration that might enhance the mixing of fuel and supersonic air with spatial forcing. For this geometrical configuration, they have conducted a numerical study with a varying amplitude of sinusoidal wave (wavy wall structure). From the predicted numerical results they found that the Mach number contours are very helpful for prediction of boundary layer separation over wavy wall and walls of the scramjet combustor.

Hongbo W et al.[2] studied numerical combustion of scramjet combustor using a passive scalar method. Flow governing equations were solved by using computational fluid dynamics tool. In this research paper, they have investigated the amount of mass transfer entry into and leaving out of the cavity which is attached to the wall of scramjet combustor. They also investigated the effect of cavity flow on residence time under reacting flow condition. Reynolds averaged Navier-Stokes equations along with large eddy simulation combination was the best simulation method to predict the flow structure of complex problems like combustion and adverse pressure gradient development flows[3-6]. It is a difficult task to sustain the flame at supersonic speed in scramjet combustor. For this different fuel injection techniques and cavities were introduced and investigated as follows; strut,[7-11], cavities,[12-15] and the combinations[16-20] with the principle of vortices generation in the vicinity of combustion chamber walls.

In supersonic flows, the mixing of fuel and supersonic air strongly depends on the residence time of supersonic air in the combustion chamber. In scramjet engines, the time available to mix and to complete the combustion is only about a tenth of a millisecond. At this residence time, mixing enhancement of fuel and supersonic air is a great challenge. Mixing of fuel and air can be increased by creating more recirculation regions, shock waves and streamline vortices along the flow field of the combustor. In this research paper, the passive technique has been implemented by creating the wall attached fuel injectors at different locations of the scramjet combustor. DLR scramjet combustor is considered as a reference or basic model to which wall attached fuel injectors are implemented.

2. Computational domain modeling

The computational domains of three different scramjet combustors are modeled with the pre-processor tool of ANSYS-FLUENT.15. DLR scramjet model[19] is considered as a basic or reference model for the development of another two models with wall attached and strut fuel injectors. The first model consists of the only wall attached strut fuel injectors and the second model consists of axial strut injector (in-line strut) along with wall attached strut fuel injectors. Computational domains of three scramjet combustors are shown in Fig.1.

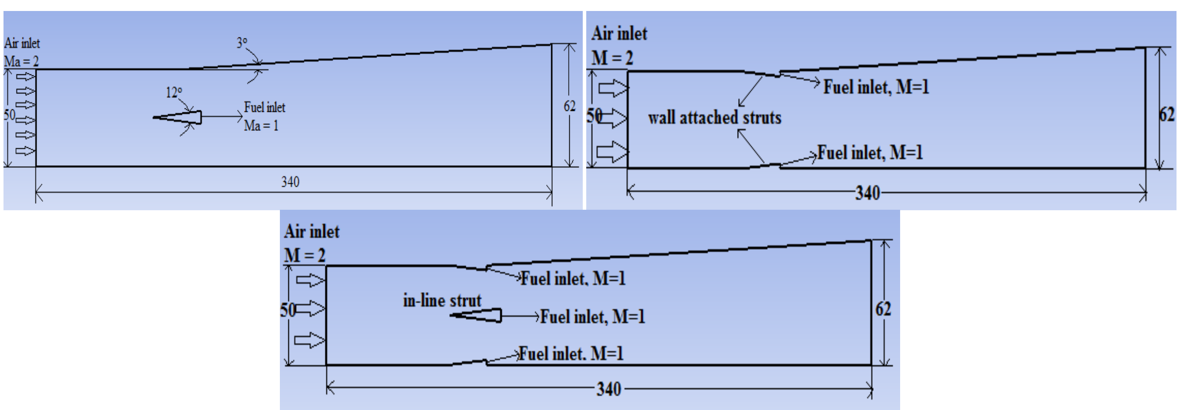

Fig.1. Scramjet computational domains: **a)** Basic model **b)** 1st model (middle) and **c)** 2nd model (bottom)

3. Numerical modeling

Two-dimensional numerical simulations have been carried out for all the computational domains. All the flow dynamics are modeled with the Reynolds averaged Navier-Stokes governing equations, SST k-w turbulence model and finite rate/eddy dissipation chemistry turbulence model.

All the flow governing equations are discretized with finite volume second order upwind discretization scheme. Stability of the iterative technique is controlled by maintaining the under-relaxation factors less than one (< 1). Global one-step reaction mechanism has been considered for the modeling of hydrogen fuel and air combustion[20]. The flow governing equations of continuity, momentum, and energy are defined as follows[20-22]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}(\tau_{ij}) \tag{2}$$

$$\frac{\partial}{\partial t}(\rho e_t) + \frac{\partial}{\partial x_i}(\rho h_t u_j) = \frac{\partial}{\partial x_i}(\tau_{ij} u_i - q_i) \tag{3}$$

Where, the variables ρ, u, τ, P, e_t, q, and h are defined as density, velocity, Reynolds stress, pressure, total energy, specific heat flux, and specific enthalpy respectively.

4. Results and discussion

Internal flow dynamics of scramjet combustor has been analyzed by performing the numerical simulations. Mixing of fuel and air at a supersonic speed greatly depends on the development of shock waves, vortices and shear mixing layer. In this paper passive technique has been implemented to enhance the mixing of fuel and air. Internal flow physics of scramjet combustor are evaluated by visualizing the density flow field, which plays a major role in the development of shock waves and recirculation regions.

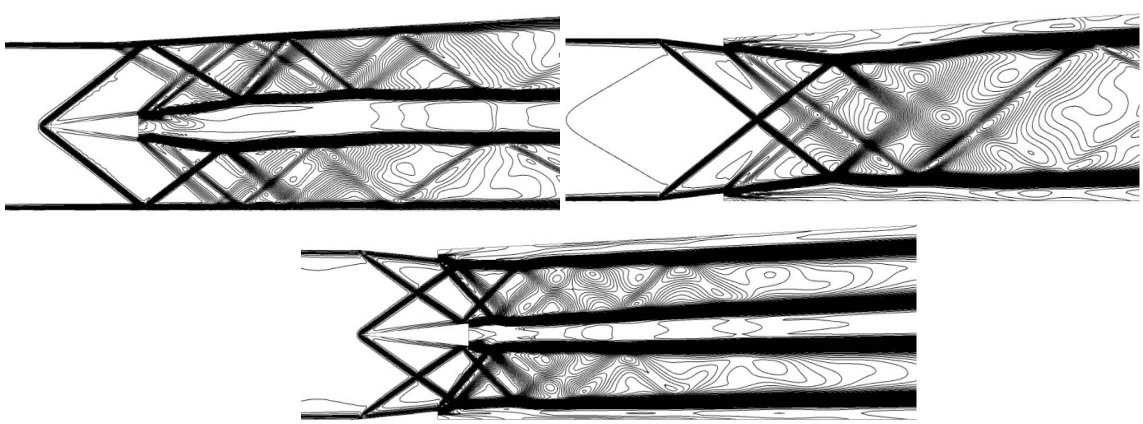

Fig.2. Density flow field of scramjet combustors: Basic model (DLR-top), 1st model (middle), 2nd model (bottom)

From Fig.2, it is observed that both oblique and expansion shock waves are developed from the leading point and trailing point of struts respectively. Both the oblique and expansion shock waves are undergone to multiple reflections in between combustion chamber wall and wake region of the strut and causes for the interaction of supersonic airstream and fuel stream and thereby enhances the tendency fuel carrying with the multiple reflection shock waves. By analyzing the density flow field of three combustors, it is identified that both the basic and 1st model has less interaction of shock waves with fuel stream as compared to the last model. The 2nd model consists of both in-line strut and wall attached strut, which are causes for more shock waves development and increases the interaction of shock waves with fuel stream and enhances the mixing of fuel and air.

To visualize more about the internal flow dynamics and complex combustion process, the temperature parameter has been considered and studied at different locations of the combustor and the same show in Fig.3. From the visualization of temperature profiles for different scramjet combustors, it is identified that the combustion phenomenon has been increased along the length of the combustor and the same observed with increase in temperature along the length of the combustor. Basic model consists of only in-line strut injector and it causes pressure losses and thereby reduces the performance of scramjet combustor. To diminish these pressure losses, 1st model is introduced with the only wall attached strut injectors. From the analysis of density flow field and temperature profile of the 1st model, it is observed that the 1st model has less performance than that of the basic model because of its fewer shocks and weak combustion. The combination of parallel fuel injection and inclined fuel injection is the best technique to enhance the mixing of fuel and air. The second model is the combination of parallel and inclined fuel injection with in-line strut and wall attached strut respectively.

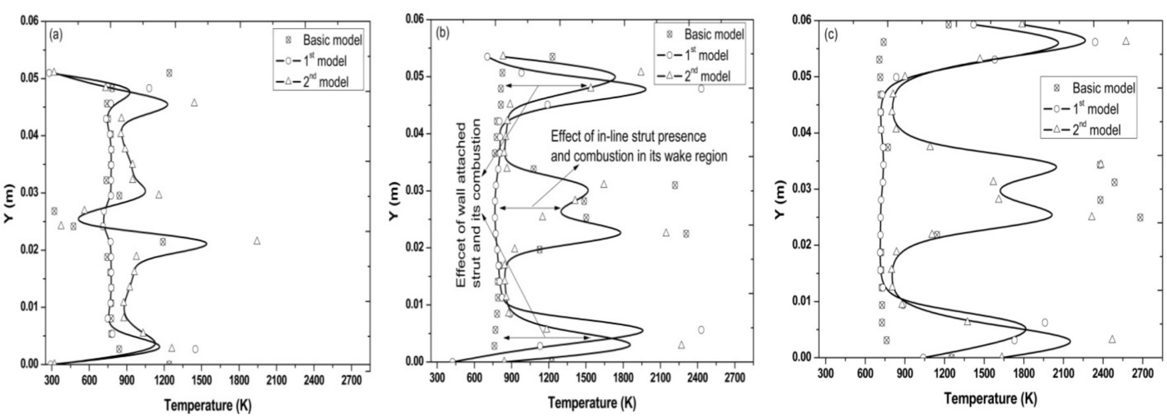

Fig.3. Temperature profiles of scramjet combustors at different locations: a) x =108 mm, b) x = 167 mm and c) x = 275 mm.

From the analysis of both density flow field (Fig.2) and temperature profiles (Fig.3) of the second model, it is identified that the development of oblique, expansion shock waves and recirculation regions are higher as compared to the other models.

5. Conclusion

Numerical analysis of scramjet combustor with in-line strut and wall attached strut fuel injector has been investigated and analyzed to visualize the internal flow field of scramjet combustor. From the analysis of both density flow field and temperature profiles for different scramjet combustors, it is identified that location of strut and fuel injection angle with respect to the mainstream plays an important role to enhance the performance of scramjet combustor. In this research paper, both the parallel and inclined strut fuel injection has been investigated. From the investigation of all three models, it is identified that the scramjet combustor with wall and in-line strut fuel injector has better performance as compared to the other two models, due to its more oblique and expansion shock waves and the combination of both parallel and inclined fuel injection technique.

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