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Numerical Simulation of Scram-Jet Combustor Using Double Wall Injector

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Abstract: development of efficient supersonic combustion scramjets is challenging with such a high speed flight within the atmosphere. The main focus of this study is to understand the fuel injection, fuel–air mixing, combustion in the high velocity and high enthalpy flow environment. A detailed cfd study was carried out to simulate the high speed reacting flows inside the combustion chamber. This paper presents the results of double wall injector having 0.295 mm diameter. The results obtained are very attractive and forced to think about the replacement of available fuel injector and enhanced the research to get more other way of fuel injection system so that the drawback of available fuel injector is completely eliminated. Using a double wall injector we get rapid air-fuel mixing with reduced pressure losses.
Key words: ramjet engine, scramjet engine, combustion efficiency, central strut injector, wall injector.

I. INTRODUCTION

A. Scramjet engines

Scramjet engine, also known as the supersonic combustion ramjet engine is an air breathing engine which can able to gain its speed theoretically as high as Mach24. An air breathing engine means combustion medium is atmospheric air. This excellent feature makes scramjet engine is a very special engine as we have no carry a tonne of oxygen cylinder during flight for the combustion process. So the weight of a whole engine reduces and scramjet engine can be able to perform its operation for long duration. Air breathing features of scramjet engine also make it smaller, faster and simpler in design.

However, working concepts of scramjets are conceptually simple, but practical implementation is limited by extreme technical challenges because of at this hypersonic speed huge amount of drag force created which develop a large quantity of frictional force. This frictional force converts into a tremendous amount of heat and start to increase the temperature of scramjet parts up to very high magnitude. So the component of scramjet is designed and selected in such a way that they can able to withstand at this condition.

Different way of propulsive system in a turbojet, ramjet and scramjet make the difference in the amount of power development and efficiency of the combustion chamber.

The scramjet is composed of three basic components:

1) Inlet- In this region of scramjet engine air is compressed and decelerated. Yet velocity of air has been supersonic. Surface of inlet may be fixed or adjustable. Various shapes and sizes used for inlet but everyone performs the same function. The design of these supersonic inlets in such a way that they can optimize the front area of scramjet.

2) Combustor- Fuel injection, air-fuel mixing, fuel ignition and combustion of fuel take place in this zone of scramjet engine. Cross sectional area of the combustor is expanding in the direction of flow for maintaining the speed up to desire value. Following parameter should be considered during designing or analyzing of the combustor are- heat losses from surfaces, conductivity of surfaces, wall shear, chemical stability of air-fuel mixture, magnitude of pressure and temperature created.

3) Diverging nozzle- Divergent duct of nozzle is used to expand the flow usually with continuing combustion reaction because of less available time and space within the combustor. As thrust produced by the engine is slightly greater than drag force, efficiency and design of the nozzle should be good for proper working of scramjet engine.

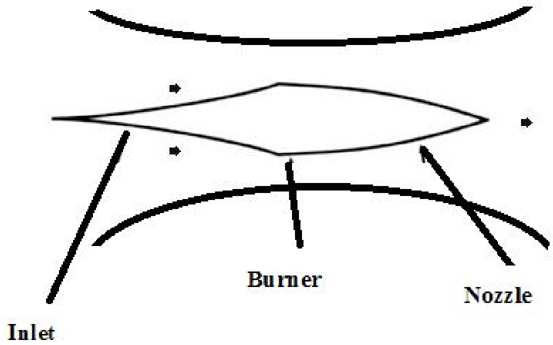

Figure1: Working Diagram of Scramjet Engine

B. Fuel of Scramjet Engine

The air within the scramjet combustion chamber are with supersonic speed. So the time available for mixing of fuel with air in appropriate proportion is less than one millisecond and poor performance of fuel injector causes a large pressure drop inside the **b** must burn enough fuel to generate a sufficient amount of energy needed to overcome the huge amount of drag forces experienced when flying at hypersonic speed. So the fuel of scramjet must be able to satisfy the above operating condition. After analyzing property of several fuels, researcher found that hydrogen as a fuel is the best candidate for scramjet combustion process. Features of hydrogen, which make it special fuel are- wide flammability range, lower heating value, exhausts after combustion are eco-friendly.

C. Type of Fuel Injector in Scramjet System

Fuel injector plays an important role in scramjet because complete power developed by scramjet depends on combustion and combustion mainly depends on the combustion chamber, combustion medium and fuel injector. Some available fuel injectors are as follows:

1) *Strut injector:* Such injectors are located at the channel axis and directly inject the fuel into the core of the air stream. Some strut injectors have a diamond shape. Diamond shape strut injector increases combustion efficiency up-to 94.2% [2].
2) *Wall injectors:* Wall injector is very popular injector because such injector able to increase combustion efficiency up-to very high magnitude with minimum pressure losses inside the combustor. Wall injector with single cavity improves the turbulence in the flow and increases the air-fuel mixing very rapidly and able to develop temperature inside the combustor up-to 2100K [3]. This excellent result forced the researcher to focus his study toward double cavity wall injector and hence group of researcher performs his work on single wall double cavity based scramjet combustor with and without aft wall angles with l/d ratio 5 and 10 [4].
3) *Ramp cavity injector:* Development of hot spots inside the combustor is major problem with wall injector without cavity. For solving this problem ramp injector is the best option available where air-fuel mixed near the core of the flow **[5].**

II. LITERATURE REVIEW

A. K. Kumaran and V. Babu [6]

studied on "Investigation of the effect of chemistry models on the numerical predictions of the supersonic combustion of hydrogen", and their observation were – Chemistry involved in the combustion is able to predict the magnitude of heat liberation inside the combustor.

B. Donna Karen Kraus [7]

performed research on "An Experimental Investigation of Mixing Enhancement in a Simulated Scramjet Combustor By Use of Swirling Jets" and they observed- fuel injection with swirl increases the air-fuel mixing rate and improve the combustion. However the penetration capacity of fuel injection with swirl was less than fuel injection without swirl.

C. Shigeru Aso et.al [8]

worked on the topic of "Fundamental study of supersonic combustion in pure air flow with the use of shock tunnel", and he introduced the world with new concept that- Pressure loss inside the combustor take place due to bow shock. Bow shock form due to large injection pressure.

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D. M. Deepu [9]

investigated on “Recent Advances in Experimental and Numerical Analysis of Scramjet Combustor Flow Fields”, and his findings are– Jet to free stream momentum flux ratio is directly proportion to the increase of jet penetration to free stream for all kind of jets.

III. METHODOLOGY

A. Governing Equation

This section is a summary of the governing equations used in CFD to mathematically solve for fluid flow and heat transfer, based on the principles of conservation of mass, momentum, and energy.

1) Conservation Equations : Conservation equations used in this simulation report are as follows:

a) Law of Conservation of Mass: Fluid mass is always conserved or in other word we can say that, the difference in the rate of mass inlet to outlet will be equal to rate of mass storage in the system. In mathematical form it can be written as- mass =constant, d/dx (mass) = 0 ....(3.1)

Conservation of mass is responsible for the birth of the continuity equation.

Continuity equation: General 3-D continuity equation without any assumption can be written as-$\partial/\partial x\,(\ell u) + \partial/\partial y\,(\ell v) + \partial/\partial z\,(\ell w) + \partial/\partial t\,(\ell) = 0$ ....(3.2)

b) Conservation of momentum- Momentum is conserved in every direction of flow. Conservation of momentum helps us to find out several unknown in simple and convenient way. Equations for conservation of momentum in different direction are as follows:

Equation for conservation of momentum in the x-direction- $\partial/\partial t\,(\ell u) + \partial/\partial x\,(\ell uu) + \partial/\partial y\,(\ell uv) + \partial/\partial z\,(\ell uw) = \partial/\partial x\,(\sigma_{xx}) + \partial/\partial y\,(\tau_{yx}) + \partial/\partial z\,(\tau_{zx})$ ......(3.3)

quation for conservation of momentum in y-direction- $\partial/\partial t\,(\ell v) + \partial/\partial x\,(\ell vu) + \partial/\partial y\,(\ell vv) + \partial/\partial z\,(\ell vw) = \partial/\partial x\,(\tau_{xy}) + \partial/\partial y\,(\sigma_{yy}) + \partial/\partial z\,(\tau_{zy})$ ......(3.4)

Equation for conservation of momentum in z-direction- $\partial/\partial t\,(\ell w) + \partial/\partial x\,(\ell wu) + \partial/\partial y\,(\ell wv) + \partial/\partial z\,(\ell ww) = \partial/\partial x\,(\tau_{xz}) + \partial/\partial y\,(\tau_{yz}) + \partial/\partial z\,(\sigma_{zz})$ ....(3.5)

c) Conservation of energy- Energy is always conserved quantity. It can neither be created nor destroyed but can change one form energy to other form of energy. Bernoulli’s equation is popular equation based on energy conservation.

Bernoulli’s equation are- $P/\ell g + V^2/2g + Z = \text{constant}$. ....(3.6)

General conservation equation of energy in Cartesian form is-

$\partial/\partial t\,(\ell E) + \partial/\partial x\,(\ell Eu) + \partial/\partial y\,(\ell Ev)\ \partial/\partial z\,(\ell Ew) = \partial/\partial x\,(u\sigma_{xx} + v\tau_{xy} + w\tau_{xz}) + \partial/\partial y\,(u\tau_{yx} + v\sigma_{yy} + w\tau_{yz}) + \partial/\partial z\,(u\tau_{zx} + v\tau_{zy} + w\sigma_{zz}) + \partial/\partial x\,\{k\partial/\partial x\,(T)\} + \partial/\partial y\,\{k\partial/\partial y\,(T)\} + \partial/\partial z\,\{k\partial/\partial z\,(T)\}$.........(3.7)

2) Sutherland’s law- Sutherland’s law is used to determine the dynamic viscosity and its general equation is: $\mu = \mu_o\,(T/T_O)\{(T_O + 120)/(T + 120)\}$ ....(3.8)

3) Gibbs Free energy- This energy is required to determine the equilibrium constants for the combined eddy dissipation and finite rate chemistry models. It was obtained for a constant pressure process by- $g_i/R = A_i\,(T\text{- } \ln t) – (B_i/2\ T^2) – (C_i/6\ T^3) – (D_i/12\ T^4) – (Ei/20\ T^5) + (F_i) – (G_iT)$ ….(3.9)

where G_i-is an additional curvefit constant,τ- shear stress, ℓ- density, T-temperature, μ- viscosity, k- thermal conductivity, σ- normal stress.

B. Reaction Mechanism

Hydrogen-air reaction mechanism occur during combustion process are as follows:

1) $H_2 + O_2 \leftrightarrow 2OH$
2) $H + O_2 \leftrightarrow OH + O$
3) $OH + H_2 \leftrightarrow H_2O + H$
4) $O + H_2 \leftrightarrow OH + H$
5) $2OH \leftrightarrow H_2O + O$
6) $2H_2 + O_2 \leftrightarrow 2H_2O$

C. Boundary Conditions

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All computations are initialized with the incoming air and the flow fields under considerations are supersonic. We use boundary conditions here for inflow, outflow and fixed walls, which are as follows:

1) *Inflow*- According to the theory of characteristics all variables are prescribed at inflow boundaries or we can say that Dirichlet boundary conditions.
2) *Outflow*- Neumann boundary conditions are used for all variables at outflow boundaries. This type of boundary condition also named as the second type of boundary condition named after Carl Neumann.
3) For fixed walls- On fixed walls, the no slip conditions are applied.

D. *Inlet Conditions*

Mass flow rate, temperature, the pressure of air are- 1.5kg/s, 340K, 100kilo-pascal and for hydrogen are- 4g/s, 250K, 100kilo-pascal respectively.

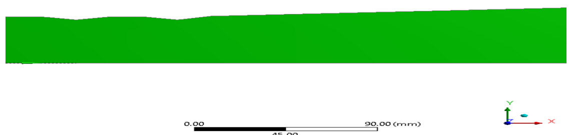

Figure-2: 2-D AxisymmetricGeometry

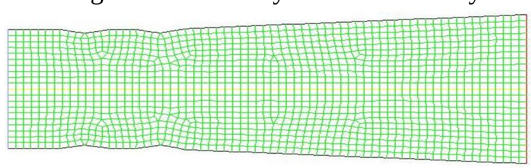

Figure-3: Meshing of 2-D Axissymmetric Geometry

IV. RESULTS & DISCUSSION

We got various result when above input given to the ANSYS fluent but our main focus of study is to analyse the temperature distribution, pressure distribution, mass fraction of water and contour of total energy which are as follows-

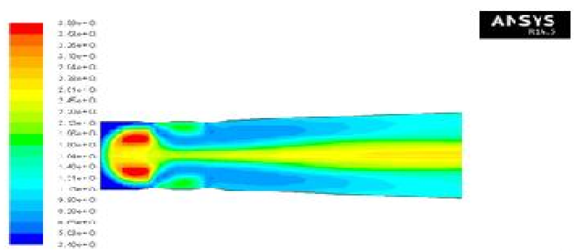

Figure-4: Contour of Temperature

The total temperature is increased at the time of injection and near the surface of injection, but its temperature is in between 3590 Kelvin near the region of injector after fuel injection done. This high value of temperature makes the strong flame stabilization and essential to heat up the combustion products up-to high magnitude.

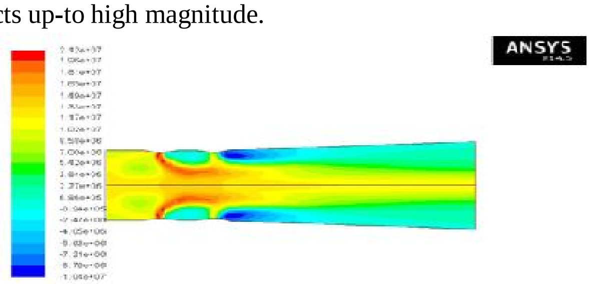

Figure-5: Contour of Total Pressure

From the above figure, it is observed that the value of total pressure gradually increases from inlet to exit the region. This high pressure developed abilities to create a higher combustion rating and finally build a huge amount of thrust which are desirable for proper functioning of scramjet. However, losses of total pressure occur due to turbulence effect, but of a very small magnitude in comparison with the total pressure development.

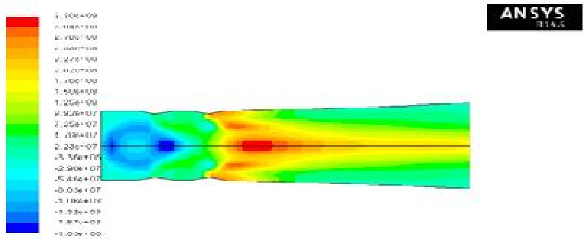

Figure-6: Contour of Total Energy

From the figure we can see that total energy changes are same in axial direction and which is near same after injection of H_2 from wall injector.

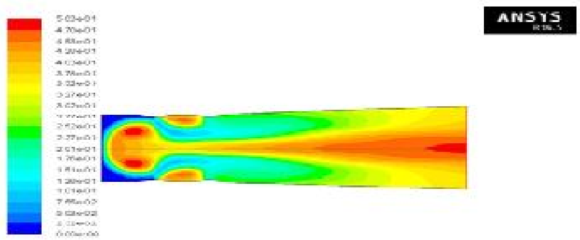

Figure-7: Contour of Mass Fraction of H_2O

After H_2 gets injected and combustion takes place, we find that mass fraction of water is continuously increases in the direction of flow. Mass fraction of water value gives the information about the water concentration distribution inside the combustor.

V. CONCLUSION

From this study, we can conclude by simulative results that this type of injector able to draw attention of several researchers to solve the problem of poor performance of available fuel injector in scramjet. From tangential velocity contours we can see the stability of flow, which is the major problem with strut injector as which provide a limitation in Mach number of engines but may give continuous flow and combustion through the flight. From pressure and temperature analysis, we can decide that this wall injector provides stability in variation in pressure and temperature through the flow condition. This work may give the solution of scramjet research vehicle in terms of correction in the stability of combustion and Mach number of engines. The future scope of this study is challenging and interesting because availability of huge options for further study like next researchers may performs his work on-more than two fuel injector, different fuels, different geometry, other flow conditions etc.

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