

# Numerical Analysis of Turbulence Mixing by Shockwave Interaction in Scramjet Combustor

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**ABSTRACT-** Supersonic combustion ramjets or scramjets offer significant performance benefits over other propulsion technologies for atmospheric flights at hypersonic speeds, as a result of their ability to extract the oxygen for combustion from the atmosphere. Supersonic combustion in scramjet is still a challenging one. The complexity of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow. This project deals with the enhancement of supersonic combustion by breaking down the streamwise vorticity and enhancing the rate of fuel air mixing in supersonic combustion. The amplification of stream wise vorticity is achieved out of the interaction between an oblique shock and fuel injector.

**KEYWORDS-** supersonic combustion, turbulence mixing, Shock wave interaction, oblique shock

## I. INTRODUCTION

An airplane propulsion system must serve two purposes. First, the thrust from the propulsion system must balance the drag of the airplane when the airplane is cruising. And second, the thrust from the propulsion system must exceed the drag of the airplane for the airplane to accelerate. In fact, the greater the difference between the thrust and the drag, called the excess thrust, the faster the airplane will accelerate. A scramjet is a variant of the ram jet air-breathing combustion jet engine in which the combustion process takes place in supersonic air flow. As in ram jet, a scramjet relies on high vehicle speed to forcefully compress and decelerate the incoming air before combustion, but whereas a ram jet decelerates the air to subsonic velocities before combustion, air flow in a scramjet is supersonic throughout the entire engine. This allows the scramjet to efficiently operate at extremely high speed: theoretical projections place the top speed of a scramjet between Mach 12 and Mach 24,

which is near orbital velocity. The mixing and diffusive combustion of fuel and air in scramjet engines take place simultaneously in the combustor. However, the incoming supersonic flow can stay in the combustor only for a very short time, which will restrict the scramjet engine design.

## I. BASIC PRINCIPLE

Shock Induced combustion ramjet engine is a new conceptual propulsion system which is similar to conventional scramjet engines using airframe integrated design, as shown in Figure 1. The oblique plane below the leading portion of the airframe is designed as an external compression or mixing – compression inlet, where the inflow is compressed. The combustor locates in the lower part of the middle section, and the posterior segment is the nozzle. Fuel is injected at the inlet, with methods to enhance the mixing efficiency of fuel and air before their entry into the combustor. Then a normal shock wave is generated by the wedge or blunt body in the front of the combustor, which ignites the supersonic mixture rapidly. This ignition and combustion mode is called shock-induced combustion.

## Numerical Analysis of Turbulence Mixing by Shockwave Interaction in Scramjet Combustor

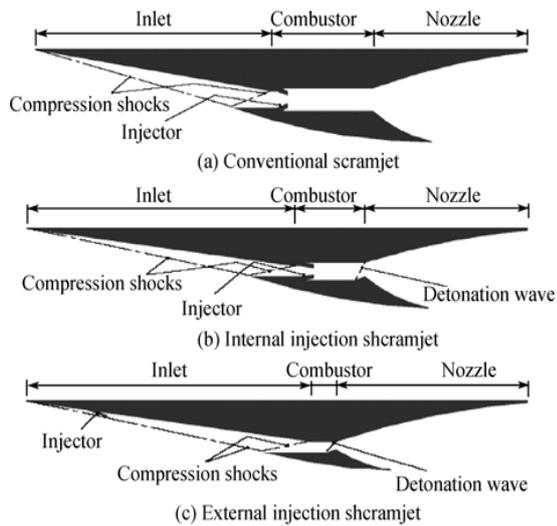


Figure 1 Hypersonic airbreathing vehicle scheme

### SCRAMJET ENGINE

Scram jets are designed to operate in the hypersonic flight regime, beyond the reach of turbojet engines, and along with ramjets, fill the gap between the high efficiency of turbojets and high speed of rocket engines. Turbo machinery-based engines, while highly efficient at subsonic speeds, become increasingly inefficient at transonic speeds, as the compressor fan found in turbojet engine require subsonic speeds can be decelerated to these conditions, doing so at supersonic speeds results in a tremendous increase in temperature and a loss in total enthalpy of the flow. Around Mach 3+, turbo machinery is no longer useful, and ram-style compression becomes the preferred method.

Ramjets utilize high speed characteristics of air to literally 'ram' air through inlet nozzle into the combustor. At transonic and supersonic flight speeds, the air upstream of the nozzle is not able to move out of the way quickly enough, and is compressed within the nozzle before being diffused into the combustor. Combustion in a ram jet takes place at subsonic velocities, similar to turbojets, but the combustion products are then accelerated through a convergent-divergent nozzle to supersonic speeds. As they have no mechanical means of compression, ramjets cannot start from a stand-still and generally don't achieve sufficient compression until supersonic flights. The lack of intricate turbo machinery allows ramjets to deal with the temperature rise associated with decelerating a supersonic flow to subsonic speeds, but this goes so far: at near hypersonic velocities, the temperature rise and inefficiencies discourage decelerating the flow to the magnitude found in ramjet engines. For a scramjet, the kinetic energy of the free stream of the air entering the scramjet engine is large comparable to the energy released by the reaction of the oxygen content of the air with the fuel. Thus the heat released from combustion at Mach 25 is around 10 percent of the total enthalpy of the working fluid. Depending on the fuel, the kinetic energy of the air and potential combustion heat release will be equal at around Mach 8. Thus the design of a

scramjet engine is as much about minimizing the drag as maximizing the thrust.

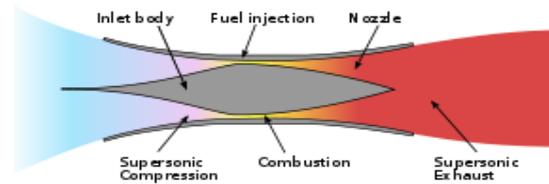


Figure 2 scram jet engine

This high speed makes the control of the flow within the combustion chamber more difficult. Since the flow is supersonic, no upstream influence propagates within the free stream of the combustion chamber. Thus throttling of the entrance to the thrust nozzle is not a useable control technique. In effect, a block of gas entering the combustion chamber must mix with fuel and have sufficient time for initiation and reaction, all the while travelling supersonically through the combustion chamber, before the burned gas is expanded through the thrust nozzle. This places stringent requirements on the pressure and temperature of the flow and requires that the fuel injection and mixing be extremely efficiency.

### SCRAMJET COMBUSTOR

Mixing, Ignition and flame holding in a scramjet combustor:

Among the three critical components of the scramjet engine, the combustor presents the most formidable problems. The complex phenomenon of supersonic combustion involves turbulent mixing, shock interaction and heat release in supersonic flow. The flow field within the combustor of scramjet engine is very complex and poses a considerable challenge in design and development of a supersonic combustor with an optimized geometry. Such combustor shall promote sufficient mixing of the fuel and air so that the desired chemical reaction and thus heat release can occur within the residence time of the fuel-air mixture. In order to accomplish this task, it requires a clear understanding of fuel injection processes and thorough knowledge of the processes governing supersonic mixing and combustion as well as the factors, which affects the losses within the combustor. The designer shall keep in mind the following goals namely,

- i. Good and rapid fuel air mixing
- ii. Minimization of total pressure loss
- iii. High combustion

### DEFINITIONS

(a) Turbulence Mixing:

When a flow of liquid or air becomes large, the streamlines become irregular and parcels of the flowing

## Numerical Analysis of Turbulence Mixing by Shockwave Interaction in Scramjet Combustor

substance begin to move in a highly irregular path while maintaining a net downstream velocity.

(b) Shock wave:

Shockwave is a large amplitude compression wave, as that produced by an explosion or by supersonic motion of a body in a medium. Across a shock there is always an extremely rapid rise in pressure, temperature and density of the flow, usually caused by a body moving supersonically in a gas.

(b) Oblique Shockwave:

An oblique shockwave, unlike a normal shock is inclined with respect to the incident upstream flow direction. It will occur when a supersonic flow encounters a corner that effectively turns the flow into itself and compresses.

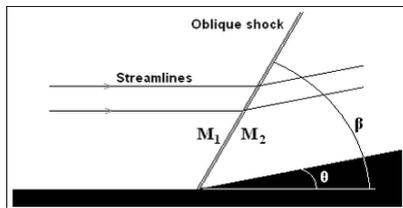


Figure 3 Oblique shockwave

### II. GOVERNING EQUATIONS FORSHOCK WAVE THEORY

A. Relations for oblique shock theory

When an object is inclined to the upstream flow direction is said to be oblique shock wave. The oblique shock relations are governed by the equations of continuity, momentum equation, energy equation and equation of state in conservation and non conservation form.

Continuity equation in non- conservation form

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{v} = 0 \dots \dots \dots (1)$$

Contiunity equation in non conservation form

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \dots \dots \dots (2)$$

Momentum equation in non conservation form

$$\rho \frac{Du}{Dt} = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \dots \dots \dots (3)$$

Momentum equation in conservation form

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{v}) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \dots \dots \dots (4)$$

Energy equation in non conservation form

$$\rho \frac{D}{Dt} \left( e + \frac{v^2}{2} \right) = \rho \dot{q} - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \rho \vec{f} \cdot \vec{v} \dots \dots \dots (5)$$

Conservation form

$$\frac{\partial}{\partial x} \left[ \rho \left( e + \frac{v^2}{2} \right) u \right] + \frac{\partial}{\partial y} \left[ \rho \left( e + \frac{v^2}{2} \right) v \right] + \frac{\partial}{\partial z} \left[ \rho \left( e + \frac{v^2}{2} \right) w \right] = \rho \dot{q} - \frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \rho \vec{f} \cdot \vec{v} \dots \dots \dots (6)$$

Equation of state

$$P = \rho RT \dots \dots \dots (7)$$

When the flow is slowed by viscous effects inside the boundary layer loss in kinetic energy obtained

due to viscous dissipation. The shock layer interacts with the boundary layer and becomes fully viscous thereby altering the shape of shock wave and pressure distribution.

Supersonic diffusers produce non-uniform flow as a result of skin-friction creating boundary layer or non-uniform compression produced by the compression surface. The Euler's equation and Navier-stokes equation both admit shocks produced.

B. Relations for Prandtl-Mayer Expansion Theory

Prandtl-Mayer expansion wave is otherwise known as an expansion wave. It consist of infinitesimal number of Mach waves. To analyse this particular change we must consider the flow angle  $\theta$ , and flow variables like M and V.

$$v(M) = \sqrt{\frac{\gamma+1}{\gamma-1}} \arctan \sqrt{\frac{\gamma-1}{\gamma+1}} \arctan \sqrt{M^2 - 1}$$

Where  $v(M)$  is knowm as the Prandtl Mayer Expansion function.

### III. METHODOLOGY

From, the literature survey proper dimensions are collected in order to generate the scram jet combustor geometry and by using GAMBIT the scramjet combustor model has to be mesh i.e, generating the grid model,after applying boundary conditions the grid model is then analysed by using FLUENT where it analyse the structured grids, From the analysed model the velocity and pressure variations are produced in terms of contours, with these contours obtained the turbulence mixing is analysed with the shock interacted inside the combustor model, the main objective of this analysis is to improve the combustion efficiency and also to achieve consistent fuel air mixing in the scarm jet combustor model.

The design methodology has been accomplished by the geometry of inlet as shown in fig.4, with this type of geometry model is then allowed

## Numerical Analysis of Turbulence Mixing by Shockwave Interaction in Scramjet Combustor

to extend upto combustor, in order to generate the mesh or grid model.

Temperature	250K
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Table 6.1 boundary condition details

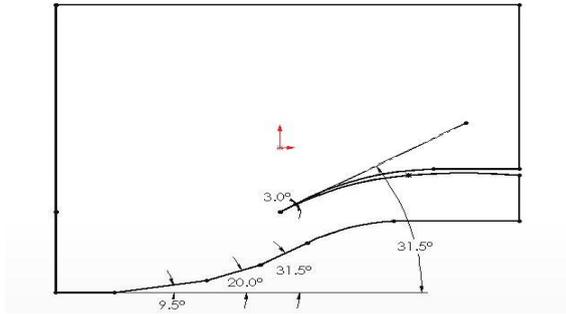


Figure 4 Geometry of Inlet

From the above geometry of the inlet is then elongated to combustor and allowed to generate the grid model.

### IV. GRID GENERATION

A structured mesh with quadrilateral elements better suited for well resolved high Reynolds number flow.

The grid model for scram jet combustor model using Gambit has been produced as shown in Figure below. This grid model has to be analysed using Fluent in order to determine the velocity and pressure variations, and also to analyse the turbulence mixing with the shockwave interaction

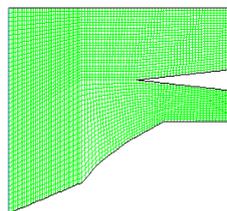


Figure 5 Grid model for a scramjet combustor model

### V. BOUNDARY CONDITIONS

In a supersonic combustion conditions, the flow variables such as velocity, stagnation pressure, static pressure, stagnation temperature and static temperature are accounted. With the given boundary conditions of velocity magnitude which is supposed to be specified as inlet, whereas pressure as the outlet. And the values given for the velocity, gauge pressure, temperature are then to be applied in a manner in order to accomplish the analysis.

Inlet	Velocity magnitude
Outlet	Pressure outlet
Gauge pressure	40000 Pa
Mach number	2.5
Velocity	852 m/s

### VI. MESH DETAILS

Mesh type	Structural Mesh
Nodes	6756
Interior faces	12895
Quadrilateral cells	6550

Table 7.1 mesh details

### VII. RESULTS OF ANALYSED MODEL

#### A. Contours of velocity magnitude:

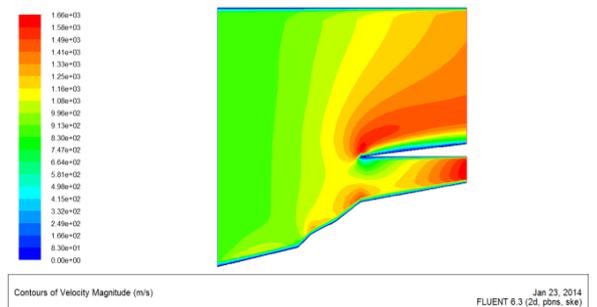


Figure 6 contours of velocity magnitude

#### B. Contours of static pressure:

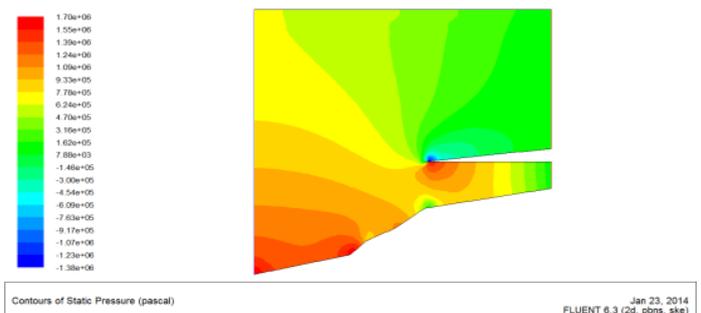


Figure 7 contours of static pressure

#### C. Contours of static Temperature:

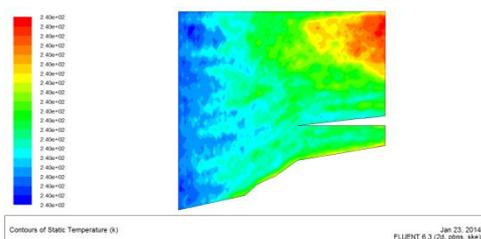


Figure 8 contours of static temperature

## Numerical Analysis of Turbulence Mixing by Shockwave Interaction in Scramjet Combustor

The above scram jet combustor model has been analysed by using FLUENT which has produced the velocity and pressure variations by generating the contours of velocity and pressure and also the temperature. By these variations in velocity and pressure, the turbulence mixing can be analysed with shock wave interacted in the combustor before injecting the fuel.

Like wise the turbulence mixing must also be analysed after the injection of fuel i.e, the turbulence mixing is to be analysed before and after placing the fuel injector in the combustor model.

### VIII. CONCLUSION

Hereby, concluded that from the above analysed model, the velocity and pressure variations which produces the shock wave interaction in the combustor model has been determined and also the turbulence mixing has been analysed with shock wave interaction before injecting the fuel. With these analysed mixing the combustion efficiency can be increased and also there will be consistent fuel air mixing.

With these above considerations, the future enhancement will be placing fuel injector in the combustor model and again the turbulence mixing is to be analysed with the shock interactions after injecting the fuel, which will result in a increased rate of fuel air mixing in the scram jet combustor model and better combustion efficiency in the combustor model.

### REFERENCES

- [1] Kermani, M. J., and Plett, E.G., 2001 "Roe Scheme in Generalized coordinates:Part I Formulation", AIAA Paper 1 2001-0086.
- [2] Duncan B., Thomas S., 1992, "Computational Analysis of Ramjet engine inlet Interaction", A.E, ASME, and ASEE, Joint Propulsion Conference and exhibit, 28<sup>th</sup>, Nashville, TN, July 6-8, 12p.
- [3] Gossping P., Lesage F., Champlain Aide., 1998, "The Application of Computational fluid Dynamics(CFD) for the Design of Rectangular Supersonic Intakes", Proceedings of CFD 98 Conference.
- [4] Goldsmith E.L., Sedona J., 1999, Intake Aerodynamics, Blackwell Science, Second Edition.
- [5] Sislian J P, Schirmer H, Dubebout R, et al. "Propulsive performance of hypersonic oblique detonation wave and shock induced combustion ramjets". J Propul Power, 2001, 17(3):599-604.
- [6] Couture D, Dechamplain A, Stowe R A, et al. "Comparison of scramjet and shcramjet propulsion for a hypersonic waverider configuration". AIAA Paper 2008-5171,2008.
- [7] Wang Y W, Sislian J P, "Numerical investigation of methane and air mixing in a shcramjet inlet". AIAA Paper, 2008-2533, 2008.
- [8] Schwartzentruber T E, Sislian J P, Parent B. "Suppression of premature ignition in the premixed inlet flow of a shcramjet". J Propul Power, 1998, 14(6): 869-879.
- [9] Sislian J P, Schumacher J. A. "Comparative study of hypersonic fuel/air mixing enhancement by ramp and cantilevered ramp injectors". AIAA Paper 99-4873, 1999.
- [10] Sislian J P, Parent B. "Hypervelocity fuel/air mixing in a shcramjet inlet". J Propul Power, 2004, 20(2): 263-272.
- [11] Heiser, W. H., Prat, D. T., Hypersonic Air breathing Propulsion, AIAA, 1994, pp. 14-22.

- [12] Mai, T., Sakimitsu, Y., Nakamura, H., Ogami, Kudo, T., Kobayahi., H., "Effect of incident shock wave interacting with transversal jet flow on the mixing and combustion". Proc. Comb. Inst. 33:2335-2342 (2011).
- [13] Builder, C., H., Prat, D.T., "On thermodynamic Spectrum of Airbreathing Propulsion". Proc AIAA 1<sup>st</sup> Annual Meeting, Washington, D. C., AIAA Paper 64-243 (1964).
- [14] Ben- Yakar, A., Hanson R. K., "Cavity flame holders for ignition and flame stabilization in scramjet:An Overview", Journal of Propulsion and Power 17:869-877, (2001).
- [15] Veraar, R.G. and Mayer, A.E.H.J., "High Speed air breathing Propulsion Systems,Research and Development at TNO", RTO-AVT Innovative Missile Systems Symposium, Amsterdam, The Netherlands, 15-19 May 2006.
- [16] Sislian, J.P., Martens, R.P., Schwartzentruber, T.E., and Parent, B., "Numerical Simulation of a Real Shcramjet flowfield", Journal of Propulsion and Power, Vol. 22, No. 5, 2006, pp. 1039-1048.
- [17] Akhgari, M., Tabejamaat, S., Seraj Mehdizadeh, "Numerical study of the effect of injection modeling on mixing and flame stability in Supersonic Combustion", Comb. Sci. and Tech. 179: 281-291 (2007).
- [18] Veraar, R.G., and Mayer, A.E.H.J., "The Role of the TNO Free jet test facility in solid fuel ramjet Projectile Development", AIAA-2005-3828, 41<sup>st</sup> AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Tucson, Arizona, USA, July 2005.