Numerical simulation of a scramjet intake with micro-cavity

Senthilkumar P*, Kamalraj Thiyagaraja
Department of Automotive Engineering, School of Mechanical Engineering, VIT University, Vellore, Tamil Nadu, India 632014
***Corresponding Author: E-Mail: psk@vit.ac.in**

ABSTRACT

Scramjets engines fill the gap between the turbojets and the high speed rocket engines. A scramjet engine allows combustion to take place at supersonic conditions by generating high pressure through the formation of an oblique shock train. . The Shock Wave Boundary Layer Interactions (SWBLI) in the inlet lead to various adverse effects like increase in flow distortion, reduced pressure recovery, decreased mass flow rate, flow separation and inlet unstart. It also results in the formation of a separation bubble that reduces the area of mass capture for proper combustion. The purpose of this study is to identify the effect on pressure loss and flow distortion by incorporating a micro cavity at the location where the separation bubble forms. A 2D CFD analysis has been performed on Ansys Fluent 15.0 to study the effect of micro cavity on various performance parameters like the Static Pressure, Pressure Recovery and Flow Distortion by comparing them with results obtained in models without micro cavity. Study was done on scramjet inlet models having both 0 and 5 cowl angles geometries and also on models with same geometries where the inlet is forcefully un-started by increasing back pressure. After running simulations, it was observed that in the presence of micro cavity, the separation bubble reduced in size leading to increase in static pressure, decrease in stagnation pressure loss and flow distortion.

KEY WORDS: Scram jet intake, shock wave boundary layer interaction, micro cavity, flow distortion.

I. INTRODUCTION

Scramjet is a variant of a ramjet engine in which the combustion takes place at supersonic conditions allowing the scramjet to operate efficiently at extremely high speeds. Scramjets 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 the high speed of rocket engines. Turbo machinery-based engines, while highly efficient at subsonic speeds, become increasingly inefficient at transonic speeds, as the compressor fans found in turbojet engines require subsonic speeds to operate. While the flow from transonic to low supersonic speeds can be decelerated to these conditions, doing so at supersonic speeds results in a tremendous increase in temperature and a loss in the total pressure of the flow. Around Mach 3–4, turbo machinery is no longer useful, and ram-style compression becomes the preferred method.

Shock Boundary Layer Interactions occur due to close coupling between a shock wave and a boundary layer and occur frequently in supersonic flows. They normally arise when a generated shock wave impinges on the surface on which there is a boundary layer. These interactions in presence of supersonic flows produce additional shock waves that has its origin within a boundary layer. SWBLI's are regions of high pressure and therefore create an adverse pressure gradient leading to its thickening followed by its separation. SWBLI's result in increased flow distortion, poor pressure recovery and decreased mass flow rate. The turbulence produced further amplifies the viscous dissipation which leads to increased drag force and decrease in efficiency of engine. They can also cause engine unstart when contraction exceeds the Kantrowitz's limit. SWBLI and Shock-Shock Interactions can also cause high localized heating with temperatures reaching in the order of 2000K

There are various challenges associated with the operation of a scramjet engine. The Shock Wave Boundary Layer Interactions (SWBLI) lead to various adverse effects like increase in flow distortion, reduced pressure recovery, decreased mass flow rate, flow separation and inlet unstart. It also results in the formation of a separation bubble that reduces the area of mass capture for proper combustion. Various methods have been employed to control SWBLI's and reduce the size of the separation bubble in order to improve the performance of the engine.

2. METHODOLOGY

For testing the effects of micro cavity on the performance of the scramjet inlet, first testing is performed on the traditional scramjet inlet without the micro cavity in order to locate the point of the separation bubble. Later simulations were performed for models with micro cavity and the results were then compared with the traditional model. Study was carried out for two models having a cowl angle of 0degree and 5 degrees. Design for the models was performed on SolidWorks 2012 for all geometries that were tested.

Meshing: On importing the models to ANSYS Fluent 15.0, a structured grid was used for all the models that were simulated. The triangle method was implemented and inflation layers were also used in order to accurately capture the SWBLI as the flow underwent compression. Inflation of first layer thickness with a maximum of 4 layers at a growth rate of 1.5 was implemented. The number of elements were controlled by the element size. The number of elements varied across the different models that were tested due to difference in geometries but were maintained around 50,000 to ensure lesser computational time but high accuracy.

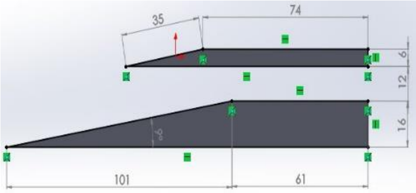

Figure.1. Geometry for inlet model with 0° cowl angle

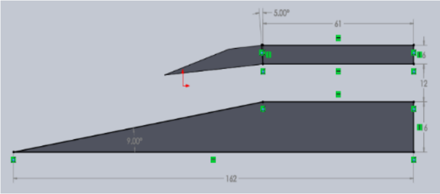

Figure.2. Geometry for inlet model with 5° cowl angle

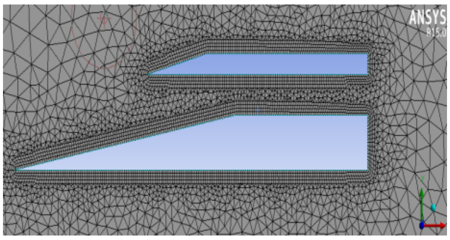

Figure.3. Generated mesh with Inflation layers have been adopted to finely capture the SWBLI

Setup in ANSYS Fluent: A density based solver is used as the simulations were carried out for compressible flow. All the models were subjected to the same boundary conditions mentioned in Table 1. Solution method used is Implicit AUSM solver. Double Precession and discretization of Second order is used to give increased accuracy. Courant number for the calculations was 0.5. Each simulation was run for a different number of iterations until a convergence was observed in the residuals graph. The results were analysed only after a converging pattern was observed.

The results obtained for 0 degree cowl angle geometry were checked verified analytically by comparing the static pressure behind the first oblique shock that is formed due to the ramp surface with the computational result obtained at the same position. The analytical verification was carried out with the help of gas tables and the following formula:

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_1^2 sin^2\beta - 1\right)$$

After the validation was completed and the results verified, the remaining simulations were performed. The turbulence model employed for running the simulations was the Shear Stress Transport (SST) turbulence model. The shear stress transport (SST) formulation combines the best of two worlds. The use of a k-ω formulation in the inner parts of the boundary layer makes the model directly usable all the way down to the wall through the viscous sub-layer, hence the SST k-ω model can be used as a Low-Re turbulence model without any extra damping functions. The SST formulation also switches to a k-ε behaviour in the free-stream and thereby avoids the common k-ω problem that the model is too sensitive to the inlet free-stream turbulence properties.

Table.1. Boundary conditions for setup in ANSYS

Location	Type	Values
Inlet, Top, Bottom	Pressure far-field	Supersonic Gauge Pressure: 12350Pa Mach Number: 3.2 Turbulence intensity and viscosity ratio: 1%, 10
Side	Wall	No-Slip conditions
Outlet	Pressure Outlet	Not edited
Symmetry	Symmetry	-

3. RESULTS AND DISCUSSIONS

After performing simulations and attainment of convergence in the model, contours of pressure, density and velocity are generated to analyse the results and compare the performance with and without micro cavity.

Scramjet intake without micro cavity: On obtaining the results, a clean shock pattern can be observed for cowl angle of zero degrees. A rise in the static pressure can be observed after each shock and then the pressure is fairly constant towards the exit of the isolator. Also a high pressure region at the shock impingement can be observed due to shock-shock interactions between incident and reflected shocks which leads to a high localized temperature.

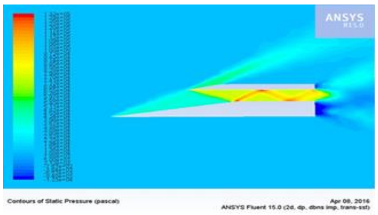

Figure.4. Pressure Contour for cowl angle 0 degree

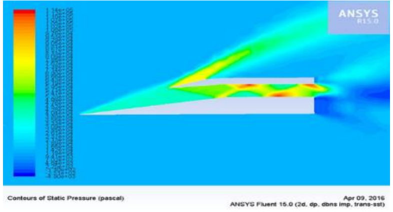

Figure.5. Pressure Contour for cowl angle 5 degree

The formation of separation bubble due to SWBLI is more evident in the results obtained above for cowl angle 5 degrees. The comparison of the performance parameters of the scramjet in the absence of the micro cavity is tabulated below.

Table.2. Performance Parameters for 0 degree and 5 degree cowl angle geometries

Parameter	Value	
	0 degree cowl	5 degree cowl
Static Pressure (bar)	.914	.857
Pressure Recovery	.532	.676
Velocity (m/s)	525	598
Loss in Stagnation Pressure (bar)	2.03	1.18

In comparison with the results obtained for Scramjet inlet with cowl angle 0 degree, the velocity at the exit of the isolator increases and the density at the same location decreases.

Scramjet intake with micro cavity: A micro cavity was placed at the point where the separation bubble forms to test the ability in reducing the separation bubble size. Reducing the size of the separation bubble can control the adverse effects of SWBLI, enabling the inlet maximize mass capture and minimize total pressure loss.

The dimensions and a sketch of the micro cavity incorporated in this study are given below.

Figure.6. Sketch of Micro Cavity, Dimensions: Height: 1.57mm; Length: 10.315mm

The height of the micro cavity was chosen in such a way that the height of the cavity was less than the height of the boundary layer. The effect of the micro cavity on the flow field and performance parameters such as static pressure and stagnation pressure were analysed.

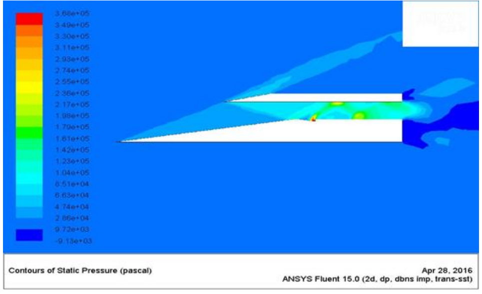

Figure.7. Pressure Contour for cowl angle 0 degree with micro cavity

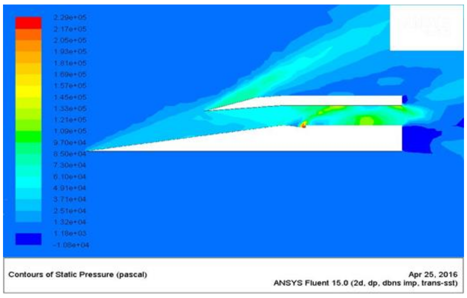

Figure.8. Pressure Contour for cowl angle 5 degree with micro cavity

From the above results, the separation bubble that was evident in the models without cavity seems to have reduced in size due to the presence of cavity at the point of its formation. The comparison of the performance parameters such as static pressure and stagnation of the inlet with and without cavity will enable us to identify the effect of micro cavity on the performance of the inlet.

Table.3. Comparison for 0degree cowl angle geometries with and without micro cavity

Parameter	Value		% Change
	Without Micro Cavity	**With Micro cavity**	
Static Pressure(bar)	.914	1.04	13.785
Pressure Recovery	.532	.944	77.4
Velocity(m/s)	525	672	28
Loss in Stagnation Pressure(bar)	2.03	0.26	-87.2

It is clear from the simulation results that the micro cavity provided an increase in the static pressure measured at the end of the isolator, it also seen that the pressure recovery increases, loss in stagnation pressure decreases.

4. CONCLUSION

A detailed numerical simulation of the scramjet inlet was carried out with and without micro cavity. Analysis on the performance parameters of the scramjet inlet such as static pressure, loss in stagnation pressure were carried out for two different cowl angle geometries. From the results obtained, it can be understood that the incorporation of a micro cavity at the point where the separation bubble forms has an effect on the performance of the scramjet intake. It is seen through simulations that:

- Micro cavity causes an increase in the performance parameters of the scramjet inlet like an increase in the static pressure measured at the end of the isolator, and a decrease of the loss in stagnation pressure.
- The separation bubble is only seen in all the simulation results obtained for the 5° geometry.

- In the presence of the micro cavity, it is seen that the size of the separation bubble is decreasing or has disappeared in comparison to the models without micro cavity.

The micro cavity improves certain parameters like increasing the static pressure at the end of the isolator, increase in pressure recovery and a decrease in flow distortion.

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