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Numerical Study on Performance of Scramjet Intake with Boundary Layer Bleed

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ABSTRACT

A Scramjet is a supersonic combustoin ramjet engine which involves supersonic combustion at high pressures through the formation of a shock train. As the air passes through the inlet it gives pressure rise to shock waves which can lead to boundary layer separation. Shock boundary layer interaction (SBLI) has a detrimental effect on the performance of the scramjet as it can lead to the formation of normal shocks. Velocity will decrease to subsonic levels which leads to engine un-starting and may ultimately cause catastrophic consequences for the engine or may even lead to the failure of flight controls. There are various methods that have been proposed to control and suppress SBLI. One of those methods is boundary layer bleed which has been studied here. Boundary layer bleed can reduce the amount of the flow separation that occurs in a normal scramjet inlet at the point of separation by means of suction or tangential blowing and can enhance its performance. A 2D CFD analysis has been performed on Ansys Fluent 15.0 to study the effect of the boundary layer bleed by means of suction on various performance parameters like the Static pressure, stagnation pressure recovery and flow distortion. This is then compared with the results obtained in models without boundary layer bleed at inlet conditions of Mach Number 3.2 and Static Pressure 12350 Pa using the SST Turbulence model in Fluent on Scramjet inlet models having both 0 and 5 cowl angles geometries. The same comparison is also done on models where the inlet is forcefully un-started by increasing back pressure . The bleed size was limited to 20% of the mass defect as the effect of the bleed on the mass flow rate entering the scramjet inlet also needed to be determined. It was observed through simulations that boundary layer bleed causes a reduction in separation bubble length and the separation bubble height while improving all the performance parameters mentioned above at the expense of the mass flow rate entering the scramjet inlet.

Keywords: scramjet intake, boundary layer bleed, flow distorsion, shock boundary layer interaction(SBLI)

I. INTRODUCTION

Scramjets are air breathing engines where combustion takes place at supersonic speeds unlike ramjet engines where the combustion takes place at subsonic speeds. They consist of an inlet, an isolator, a combustor and a nozzle. As such the scramjet engine doesn't require any moving parts, and the absence of such rotating components allows the engine weight to be reduced and decreases the number of potential failure points. A common problem encountered in all hypersonic air-breathing engines is the Shock Boundary Layer Interactions (SBLI) which causes flow separation due to the presence of adverse pressure gradient. It leads to increase in aerodynamic drag and aerodynamic heating, flow unsteadiness, an increase in stagnation pressure loss, a decrease in static pressure at the exit, increased instabilities such as inlet buzz and flow distortion which can lead the engine to un-start and have catastrophic consequences and ultimately lead to a loss in the overall performance and efficiency of the aircraft. There are various ways that have been proposed over the years to control the problem posed by SBLI.

The methods used to curb the problem of SBLI are classified into two categories: Active control and Passive Control. Passive Control includes use of protuberances such as micro-vanes and micro-vortex generators, stream-wise slots/bumps to tackle the problem of SBLI. Active Control methods include the

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use of micro-jets and boundary layer bleed (by suction or tangential blowing) at the point of separation to control SBLI. Boundary layer bleed causes the removal of the low energy part of the boundary layer which leads to a decrease in the boundary layer thickness and reduces the separation, leading to a decrease in total pressure loss. This with addition of the simplicity and cost effectiveness of boundary layer bleed makes it a good method to be investigated for the control of SBLI.

Scramjet engines are a relatively new technology when compared with the other propulsion systems. They are different from turbofan, turbojet and rocket engines as they have no moving parts and the oxygen required for combustion is taken from the atmosphere instead from a tank onboard. Scramjet engines can be classified as a development over the ramjet engines where the flow is slowed down from supersonic to subsonic speeds by the means of a normal shockwave and the combustion occurs at subsonic speeds. But, the occurrence of a normal shockwave leads to a high loss in stagnation pressure and temperature. To overcome this problem, scramjet engines utilize an oblique shock train in order to achieve the required pressure rise need for combustion. This project aims to study the effect of boundary layer bleed - an active control method to control SBLI on the starting and un-starting capabilities of the scramjet inlet and study the effects of the boundary layer bleed on the performance parameters of scramjet by analyzing the static pressure, stagnation pressure loss and flow distortion. The effect of the bleed on SBLI will also be investigated and an attempt will be made to analyze how the size of the separation bubble varies with the bleed..

II. METHODOLOGY

The goal of this project is to analyze the effect of boundary layer bleed on the performance and starting capacities and capabilities of the scramjet inlet and analyze whether by the use of boundary layer bleed can the problem of unstarting be completely eliminated. In order for us to provide a boundary layer bleed and study its effects on the scramjet performance, it is required to first identify the point of separation and measure the size of the separation bubble that will be formed in a traditional scramjet inlet. Thus, the project has been divided into different stages in order to achieve the targeted functionality: Testing the traditional scramjet inlet model through CFD simulations to identify the shock patterns, point of separation and the performance of the scramjet inlet at two different configurations. Forcibly unstarting the inlet by providing a blockage and analyzing how the shock patterns and the performance of the scramjet inlet varies at the different configurations. Providing the bleed at the required point on the boundary layer and performing the simulations to study the boundary layer's effect on the performance for the different configurations. Comparing the results obtained with and without boundary layer bleed to identify the changes obtained in the performance of the scramjet inlet. The different geometries being tested have cowl angles at 0° and 5° and the inlet was forcibly unstarted by increasing the back pressure by means of providing blockage, the inlet exit was blocked by 33.33% to simulate this effect. Through simulations on Ansys 15, the contours of static pressure, density and velocity were analyzed and the different performance parameters such as loss in stagnation pressure, flow distortion and static pressure were analyzed between different the models of with and without bleed at both 0° and 5° configurations.

(A) Setup in Ansys

For the setup in ANSYS Fluent 15.0, the flow is first considered to determine the settings. As the flow is compressible in supersonic flow a density based solver is employed to finely capture the generated boundary layer under adverse pressure conditions. It is also to be noted that all the models that are being simulated are subjected to the same boundary conditions which are defined in table 6.2. For the models with bleed there was another condition that needed to be added at the point of bleed to initiate the required suction. The setting was initiated as "Outlet-vane" in order for suction to occur from this bleed slot and the pressure was set at 0100^(-5) Pa.The outlet pressure can't be predicted at the beginning of the calculations and thus its value isn't edited. 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. Iterations were run till the residuals became constant, a sign that convergence has occurred in the simulations. This took approximately 5000 iterations to occur, after which the contours were obtained and the results were analyzed. The results obtained for 0° 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. After the validation was completed and the results verified, the remaining simulations were performed.

Table 1
Boundary conditions for setup in ANSYS

Location	*Type*	*Values*
Inlet, Top, Bottom	Pressure far-field	Supersonic Gauge Pressure: 12350 Pa
		Mach Number: 3.2
		Turbulence Intensity: 1%
		Viscosity Ratio: 10
Side	Wall	No-slip conditions
Outlet	Pressure Outlet	Not edited
Symmetry	Symmetry	-

(B) Design Approach

Using Fluent Solver in ANSYS 15.0 simulations are performed using the SST (Shear Stress Turbulence Model) until convergence was achieved. The SST model was preferred because it can simulate compressible flows accurately and capture the boundary layer that is formed well. It is a combination of the k-ω and the k-ω models where the k-ù is used to model the inner part of the boundary layer and the k-ω formulation is used for modeling the free-steam flow, thus giving a smooth transition that stands out better than what is achieved by the use of other available turbulence models. The computational result obtained behind the first shockwave for the 0° cowl angle was verified with the values obtained behind the first shockwave analytically using Gas Tables for Compressible flows. After the data validation was completed, simulations were performed for models containing bleed and blockages and the results analyzed.

III. RESULTS AND DISCUSSIONS

After performing simulations and attainment of convergence in the model, different contours are generated to analyze the results.

(A) Scramjet inlet without bleed

To test the effect of back pressure unstart on the performance of the scramjet inlet a blockage was provided with the dimensions which leads to a blockage of 33.33% of the isolator exit. The blockage was provided for both the 0° and 5° cowl angle geometries and the boundary conditions for the test were kept same. After simulation was complete and convergence was attained the static pressure contours were generate. It is clear from analyzing these contours that blockage increases the isolator exit pressure and also decreases the velocity, due to the formation of an extra shock because of the blockage which also slows the velocity of the flow with which the air leaves the isolator when compared to the models with no blockage. The dimensions of the separation bubble formed for the 5° cowl angle geometry with blockage has a height of 5.66 mm and a length of 22.64 mm. The results obtained here are used for comparing how the boundary layer bleed influences the unstarting of the scramjet inlet caused by high back pressure.

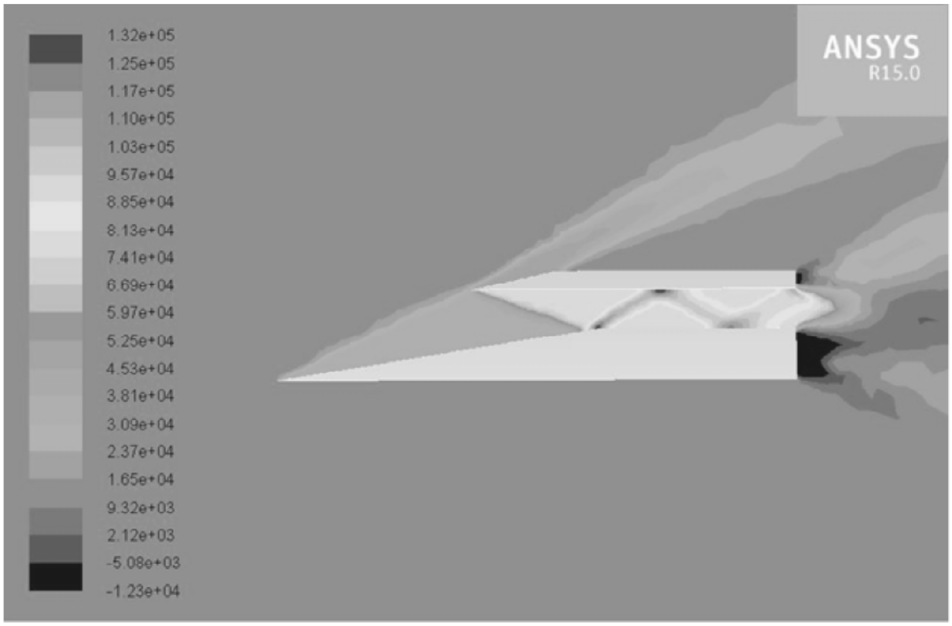

Figure 2: Static Pressure Contours for Scramjet inlet with cowl angle 0°

Table 2
Performance Parameters for 0° and 5° cowl angle geometries

S.No	*Parameter*	*Value*	
		0° cowl	*5° cowl*
1.	Static Pressure(bar)	.943	.905
2.	Pressure Recovery	.534	.525
3.	Velocity(m/s)	465	504
4.	Flow Distortion	.492	.905
5.	Loss in Stagnation Pressure(bar)	1.6667	1.7887
6.	Mass Flow rate(kg/s)	.283	.178

Table 3
Performance Parameters for 0° and 5° cowl angle geometries with blockage

S.No	*Parameter*	*Value*	
		0° cowl	*5° cowl*
1.	Static Pressure(bar)	1.87	1.24
2.	Pressure Recovery	.438	.492
3.	Velocity(m/s)	402	431
4.	Flow Distortion	1.82	1.75
5.	Loss in Stagnation Pressure(bar)	3.884	2.534
6.	Mass Flow rate(kg/s)	.234	.162

(B) Scramjet inlet with bleed

First it is required to calculate the size of the bleed to be provided, this is done by calculating the mass defect caused due to the formation of the separation bubble in the 5° cowl angle geometry without blockage. The mass defect can be represented as $\dot{m}1 - \dot{m}2 = \rho v(A1-A2)$ at the point of maximum height of the separation bubble for the 5° cowl angle geometry without blockage.

At this point,

ρ = .714 kg/m3 v = 764 m/s

A1 = 3.48 X 10-4 m2 A2 = 1.595 X 10-4 m2

Thus, the mass defect, ṁ1- ṁ2= .102825 kg/s

Amount of air to be bled is taken to be 20% of this mass defect = .020565 kg/s. Thus the size of the bleed slot calculated using ρAv is found to be 1.3mm. This bleed of 1.3mm length was provided 10.35 mm downstream of the end of the ramp surface to make sure that it lies in the middle of the separation bubble that is generated in the 5° cowl geometry. This boundary layer bleed was provided for all the models that were previously tested and simulations were run again to analyze how the bleed affects each of these models.

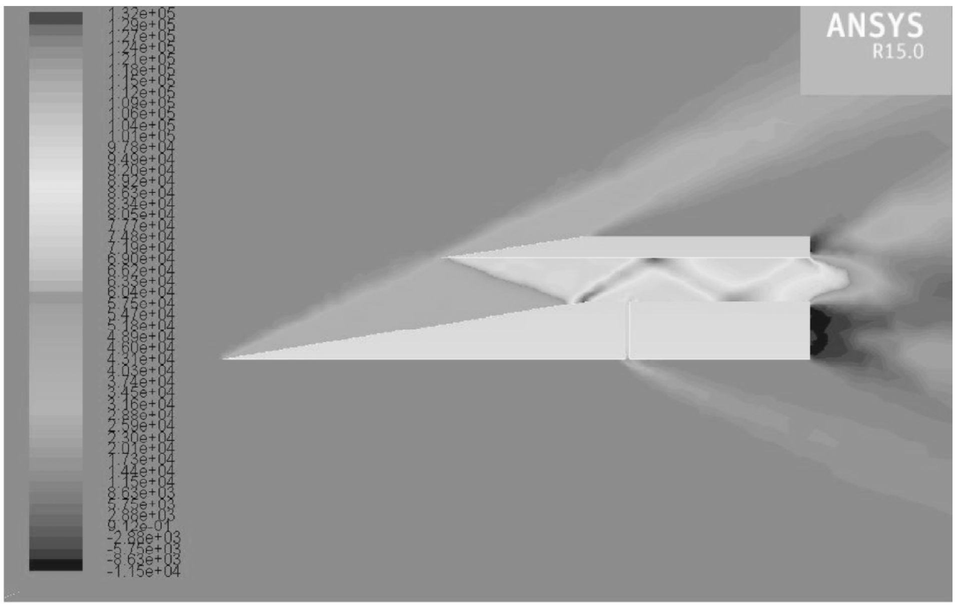

Figure 3: Static Pressure Contours for Scramjet inlet with cowl angle 0° and bleed

Table 4
Parameters for 0° cowl angle geometries with bleed

S.No	*Parameter*	*Value*	
		Without Blockage	*With Blockage*
1.	Static Pressure(bar)	1.04	2.03
2.	Pressure Recovery	.5744	.542
3.	Velocity(m/s)	475	477
4.	Flow Distortion	.738	2.06
5.	Loss in Stagnation Pressure(bar)	1.66	3.055
6.	Mass Flow rate(kg/s)	.271	.2239

Table 5
Parameters for 5° cowl angle geometries with bleed

S.No	*Parameter*	*Value*	
		Without Blockage	*With Blockage*
1.	Static Pressure(bar)	.9133	1.315
2.	Pressure Recovery	.560	.548
3.	Velocity(m/s)	497	484
4.	Flow Distortion	1.293	2.145
5.	Loss in Stagnation Pressure(bar)	1.566	2.0257
6.	Mass Flow rate(kg/s)	.167	.148

It is clear from the simulation results that the boundary layer bleed 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. The density and velocity contours for these models are provided in the Appendix. It is also seen that the separation bubble size for 5° cowl angle geometries with bleed varies from the previous models and it has a height of 5.5 mm and a length of 21.9 mm for 5° cowl angle geometry with bleed and without blockage. For the 5° cowl angle geometry with bleed and blockage the height of the bleed is 4.59 mm and the length is 19.04 mm. These results are now compared with the results obtained for the models without bleed to see the change in the performance parameters that is taking place. These compared results for all the four models tested with and without bleed calculated at the end of the isolator are provided in the Tables 5, 6, 7 and 8, the Figures 16 - 23 show graphical representation of the compared data. The variation in the separation bubble dimensions obtained for the different 5° cowl angle geometries which were simulated

(C) Comparison of results

Table 5
Comparison For 0° Cowl Angle Geometries With And Without Bleed

S.No	*Parameter*	*Value*		*% Change*
		Without Bleed	*With Bleed*	
1.	Static Pressure(bar)	.943	1.04	10.286
2.	Pressure Recovery	.5344	.5744	7.485
3.	Velocity(m/s)	465	475	2.150
4.	Flow Distortion	.492	.738	50
5.	Loss in Stagnation Pressure(bar)	1.6667	1.66	-0.42
6.	Mass Flow rate(kg/s)	.283	.271	-4.240

Table 6
Comparison for 5° Cowl Angle Geometries with and Without Bleed

S.No	*Parameter*	*Value*		*% Change*
		Without Bleed	*With Bleed*	
1.	Static Pressure(bar)	.905	.9133	0.917
2.	Pressure Recovery	.525	.560	6.667
3.	Velocity(m/s)	504	497	-1.33
4.	Flow Distortion	.905	1.293	42.87
5.	Loss in Stagnation Pressure(bar)	1.7887	1.566	-12.45
6.	Mass Flow rate(kg/s)	.178	.167	-6.179

Table 7
Comparison for 0° Cowl Angle Geometries with Blockage and with and Without Bleed

S.No	*Parameter*	*Value*		*% Change*
		Without Bleed	*With Bleed*	
1.	Static Pressure(bar)	1.87	2.03	8.556
2.	Pressure Recovery	.438	.542	23.74
3.	Velocity(m/s)	402	477	18.65
4.	Flow Distortion	1.82	2.06	13.18
5.	Loss in Stagnation Pressure(bar)	3.884	3.055	-21.34
6.	Mass Flow rate(kg/s)	.234	.2239	-4.316

Table 8
Comparison for 5° Cowl Angle Geometries with Blockage and with and Without Bleed

S.No	*Parameter*	*Value*		*% Change*
		Without Bleed	*With Bleed*	
1.	Static Pressure(bar)	1.24	1.315	6.048
2.	Pressure Recovery	.492	.548	11.382
3.	Velocity(m/s)	431	484	12.296
4.	Flow Distortion	1.75	2.145	22.57
5.	Loss in Stagnation Pressure(bar)	2.534	2.0257	-20.05
6.	Mass Flow rate(kg/s)	.162	.148	-8.641

Table 9
Comparison the separation bubble dimensions for 5° cowl angle geometry without blockage

S.No	*Parameter*	*Value*		*% Change*
		Without Bleed	*With Bleed*	
1.	Length (mm)	22.5	21.9	-2.667
2.	Height (mm)	6.5	5.5	-15.384

Table 10
Comparison the Separation Bubble Dimensions for 5° Cowl Angle Geometry with Blockage

S.No	*Parameter*	*Value*		*% Change*
		Without Bleed	*With Bleed*	
1.	Length (mm)	22.64	19.04	-15.90
2.	Height (mm)	5.66	4.57	-19.25

From the comparison of results it is evident that the boundary layer bleed has an effect on the performance parameters of the scramjet inlet and it leads to an increase in the Static pressure, pressure recovery, flow distortion, a decrease in the stagnation pressure loss and increase in velocity (except for in the case of 5° cowl angle geometry) but a decrease in the mass flow rate. The greatest difference in the performance parameters occurs in the models where blockage has been provided to simulate back pressure unstart. Furthermore, there is a decrease in the size of the separation bubble that is being formed when boundary layer bleed is introduced in all of the different 5° cowl angle geometries been tested which proves that boundary layer bleed can be used to solve the problem of Shock Boundary Layer Interaction.

II. CONCLUSION

A detailed numerical simulation of the scramjet inlet has been performed with and without boundary layer bleed. Analysis on the performance parameters of the scramjet inlet such as flow distortion, static pressure, loss in stagnation pressure were carried out for two different cowl angle geometries. It is evident that the boundary layer bleed of 20% of the mass defect has an effect on the performance of the scramjet inlet and the separation that is occurring in the inlet. It is seen through simulations that boundary layer bleed 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, increase in flow distortion 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.

With the boundary layer bleed, it is seen that the size of the boundary bubble is decreasing in comparison to the models without bleed. The boundary layer bleed improves certain parameters like increasing the static pressure at the end of the isolator, increase in pressure recovery and a decrease in stagnation pressure. But, the flow distortion increases and the mass flow rate in the scramjet inlet decreases due to a portion of the air being sucked out by the bleed leaving less air to exit the scramjet isolator.

APPENDIX

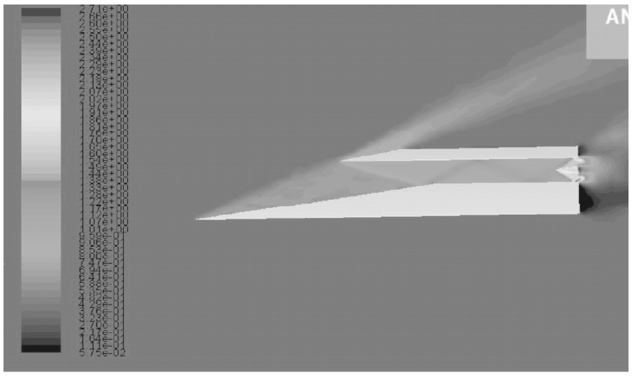

Figure 4 : Density Contours for Scramjet inlet with cowl angle 0° and blockage

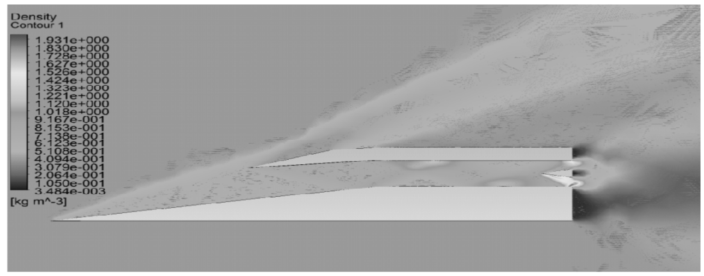

Figure 5 : Density Contours for Scramjet inlet with cowl angle 5° and blockage

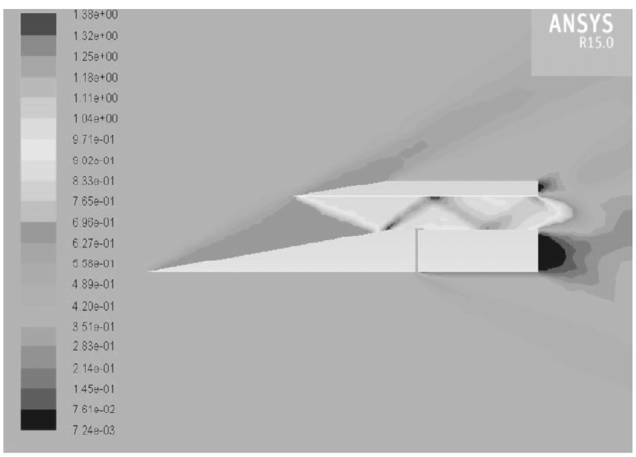

Figure 6 : Density Contours for Scramjet inlet with cowl angle 0° and bleed

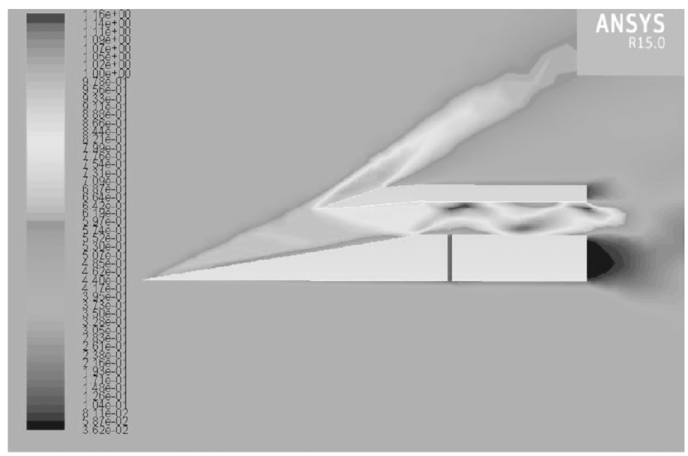

Figure 8 : Density Contours for Scramjet inlet with cowl angle 5° and bleed

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