International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 2 Issue 6, June - 2013

Effect Of Inlet Performance And Starting Mach Number On The Design Of A Scramjet Engine

P. Karthikeyan[1], B. Prakash[3 2], S. R. Balakrishnan [3]

PG scholar[1], Professor[2], Director/H.O.D[3]

[1,2,3]Department of Aeronautical Engineering, Nehru Institute of Engineering and Technology

Abstract

Since scramjets are still in developing stage and associated with technical challenges, this project deals with the effect of inlet performance and starting Mach number on the design of a scramjet engine. The concept of lower starting Mach number enables use of two propulsion systems to complete the entire mission and also enables reduction in overall weight of the system. Options for reducing the starting Mach number mainly relies on introducing variable geometry features according to the flow rate. Choice of key design parameters could also reduce the starting Mach number. The first case deals with the design of scramjet inlet for standard dimensions, followed by designs with variable geometry (cowl lip). The latter case deals with the theoretical calculations of the design parameter based on the governing basic equations of scramjet system. The analysis was done for various designs including standard geometry of inlet with different Mach numbers. Likewise the performance of variable geometry was estimated by computational methods through CFD package. A comparison was made between theoretical and computational approaches and their similarities were shown and effective one was chosen.

Keywords-*starting Mach number,variable geometry,standard inlet*

1. Introduction

Scramjet propulsion system consists of five major engine and two vehicle components. The five major engine components are: internal inlet, isolator, combustor, internal nozzle and the fuel supply subsystem.

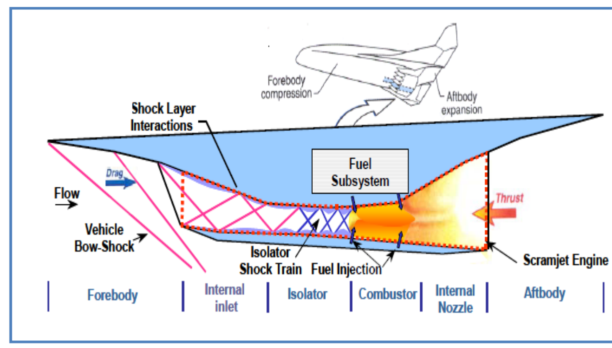

Fig 1.Scramjet Propulsion System

The vehicle components are the vehicle fore body and the vehicle aft body. The vehicle fore body is an essential part of the air induction system while the vehicle aft body is a critical part of the nozzle component.

The primary purpose of the high-speed air induction system, comprised of the vehicle fore body and internal inlet, is to capture and compress air for processing by the remaining components of the engine. The fore body provides the initial external compression and contributes to the drag and moments of the vehicle presented by Dean Andreadis.

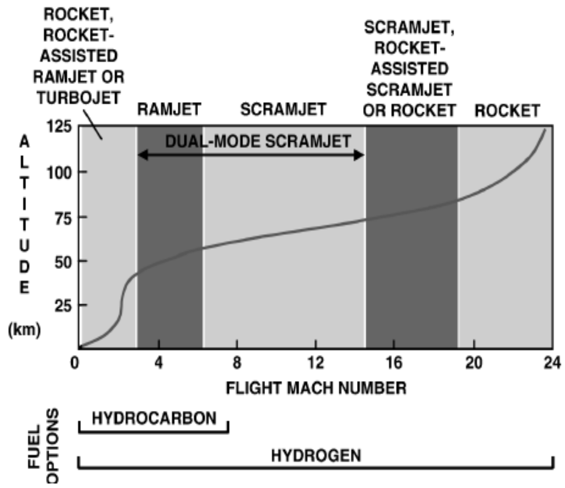

Fig 2.Propulsion System Options as a Function of Mach Number

Figure displays a qualitative chart of the propulsion options based on the flight Mach number given by Nicole Roberts. The curve represents the approximate altitude required to operate at a given flight Mach number as well as the needed propulsion system. Also shown on this chart is a relative boundary between the two primary fuel options for scramjets: hydrocarbons and hydrogen. Though Waltrup concludes that the upper limit for hydrocarbons is between Mach 9 and 10 as opposed to Fry's diagram displaying approximately 8, the general consensus is that hydrogen fuel should be used for air breathing flight faster than Mach 8-10, due to its "higher cooling capacity" and its "faster reactions". Though hydrogen can perform at higher speeds above the hydrocarbon upper limit, Curran states that with current capabilities the hydrogen fuelled scramjet will only offer "acceptable performance to about Mach 15"

Compared to rockets, scramjets have much higher specific impulse levels; therefore, it is advantageous to develop the scramjet. Contrary to rockets, scramjets do not require that an oxidizer be carried on board the aircraft as it is an air breathing engine, collecting oxygen from the atmosphere. This decreases the required weight of the overall propulsion system and fuel, resulting in a higher allowable payload weight or increased range. There are other reasons that the development of the scramjet is advantageous as well. Air breathing engines produce higher engine efficiency, have a longer powered range, possess the ability for thrust modulation to ensure efficient operation, have higher manoeuvrability and are completely reusable.

Before setting out in the analysis, it is firstnecessary to establish the reference station designations of the scramjet engine. Using Heiser and Pratt's designations, Figure show the designation system used throughout this paper.

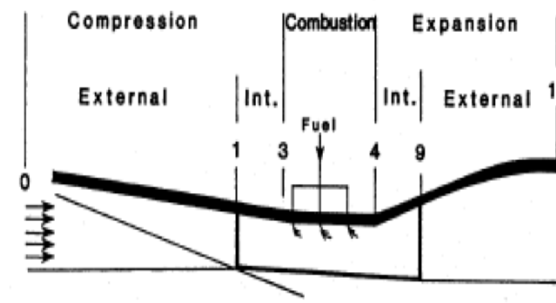

Fig 3. Scramjet engine designations

2. Description of the current work

2.1 Options for lowering the starting Mach number

As previously discussed, there is a need for the starting Mach number of the scramjet to be reduced. There have been a few projects which sought, at least in part, to lower the scramjet starting Mach number, the most extensive being HyTech. The main objective of that program is to "enable sustained hypersonic flight for missile or aircraft applications and to develop and demonstrate Mach 4-8 hydrocarbon-fuelled, actively cooled scramjet engine technology". The program has been successful in demonstrating Mach 4.5 and 6.5 ground testing. The project described in this paper, however, seeks to lower the starting Mach number to 3.50 and to determine the main factors influencing this ability. There are a number of possible ways to lower the starting Mach number of the scramjet.

2.1.1 Variable geometry

In a variable geometry scramjet, the flow path is changed according to the free stream Mach number to ensure high performance values throughout a wide range of Mach numbers. An example of a program which employed this technique is the HRE program which developed a flight-weight hydrogen-fuelled scramjet designed to operate from Mach 4 to 7 using variable geometry. Though this technique ensures high performance, it is highly complex and instils a high level of inherent risk, as it relies on a large number of moving parts which require large actuation forces.

2.1.2 Manipulation of "pure" scramjet engine key design parameters

There are a few key parameters of the "pure" scramjet engine—that is, a scramjet with one combustor and a non-variable flow path that are able to be varied and manipulated to perhaps lower the starting Mach number of a scramjet. For instance, as the cycle static temperature ratio (T_3/T_0) increases, the Mach number of the flow entering the burner (M_3) decreases. Thus, T_3/T_0 directly affects the free stream Mach number (M0) at which the flow entering the burner (M_3) becomes supersonic. Due to this, it is possible that the manipulation of T_3/T_0 would yield a lower free stream Mach number at which supersonic combustion can occur. Additionally, the key design parameters of fuel selection and fuel-to-air ratio (*f*) for the scramjet may have an impact on the starting scramjet Mach number.

3. Analysis of Key Design Parameters to reduce Scramjet starting Mach number

This chapter will detail the theory and equations necessary as well as the analysis completed towards developing a scramjet with a lower starting Mach number.

Performance Analysis Inputs	How Determined
Mo, Vo, To, P_0	Set by Mach Number
C_{pc}, R, C_{pb}, C_{pe}, h_f, g_o	Constant
V_{fx}/V_3, V_f/V_3, $C_f(A_w/A_3)$, n_c, n_b, n_e, T_o, p_{10}/p_0, γ_c, γ_e, γ_b	Assumed
T_3/T_0, f, h_{pr}	Variation

Table 1. Performance Analysis Inputs and Corresponding Determination Methods

The constant values of some of the inputs used for analysis and are given as below:

Constants		
C_{pc}	1090.00	J/kgK
R	289.3	$m/s^2/K$
C_{pb}	1510.00	J/kgK
C_{pe}	1510.00	J/kgK
h_f	0.00	---
g_o	9.81	m/s^2

Table 2. Stream Thrust Inputs: Constant Values

The assumed values of given inputs used for analysis and they are given as below:

V_{fx}/V_3	0.50
V_f/V_3	0.50
$C_f(A_w/A_3)$	0.10
η_c	0.90
η_b	0.90
η_e	0.90
T_o	222.00
p_{10}/p_0	1.40
γ_c	1.362
γ_e	1.238
γ_b	1.238

Table 3. Stream Thrust Inputs: Values for Assumed Values

3.1 Theoretical Calculations

Input conditions were taken as same as in the previous trial

$$\mathbf{T_o = 271.06\ K,\ P_o = 0.95\ bar,\ M_o = 4}$$

From the definition of Mach number,

$$M_o = V_o/a_o$$

$$V_o = M_o * a_o$$

$$= 1320\ m/s$$

From the reference paper [5] the formula obtained below is of the form

$$M_3 = \sqrt{2/\gamma c\text{-}1\{To/T3(1+\gamma c\text{-}1/2*Mo^2) - 1\}}$$

Assume the value of M_3= 1 and γc=1.362

$$1 = \sqrt{5.525\{To/T_3(3.896)-1\}}$$

$$4.64\sqrt{To/T_3}-2.35 = 1$$

$$\sqrt{To/T_3} = 3.35/4.64$$

$$To/T_3 = 0.521$$

$$T_3 = 519.89\ K$$

Compression component:

1. Stream thrust function (Sao)

   $$Sao = Vo\ (1+RTo/Vo^2)$$

   $$= 1320(1+287*271/1320^2)$$

   $$= 1378.92$$

2. Combustor entrance temperature

   $$T_3 = \varphi\ To$$

   $$\varphi = T_3/ To$$

   $$= 1.92$$

3. Combustor entrance velocity

   $$V_3 = \sqrt{Vo^2 - 2CpcTo(\varphi-1)}$$

   Where C_{pc} is 1090 J/kg K

$V_3 = 1094.93$ m/s

4.Stream thrust function at combustor entrance

$$Sa_3 = V_3(1+RT_3/V_3^2)$$

$$=1094.9(1+287*1002.2/(1094.9)^2$$

$$= 1231.17$$

5.Ratio of combustor entrance pressure to free stream pressure

$$p_3/po= \{ \varphi / \varphi(1-\eta c)+ \eta c \}^{Cpc/R}$$

Take the value of ηc as 0.9 (reference paper)

$$p_3/po = 8.52$$

6.Ratio of combustor entrance area to free stream entrance area

$$A_3/Ao = \varphi * po/p_3*Vo/V_3$$

$$A_3/Ao= 1.92*0.117*1.2$$

$$= 0.271$$

From the calculation we came to know about the effect of Mach number by showing the results.

S.NO	M_O	T_3 (K)	T_3/T_O	V_3 (m/s)	P_3/P_O
1	7	1314.3	4.85	1749.98	115.35
2	6	948.2	3.69	1526.8	57.29
3	4	519.89	1.92	1094.93	8.92

Table 4.Parameters at station 3

4. Scramjet Inlet Design

The goal of the compression system in a scramjet engine is to "provide the desired cycle static temperature ratio (T3/T0) over the entire range of vehicle operation in a controllable and reliable manner with minimum aerodynamic losses (i.e., maximum compression efficiency or minimum entropy increase". This compression, for the one-dimensional analysis used throughout this project, relies on oblique shock waves. Normal shock wave compression is reserved for ramjets as it is able to offer "reasonable performance for 0 < M0 < 3," whereas for Mach numbers greater than 3, the "normal shock losses become unacceptably high and oblique shock compression becomes necessary". As an internal compression system is highly complex in design, the choice for this project is between an external compression system and a mixed internal and external compression system. The decision between these two options is generally based on practical integration issues. Since this project is a preliminary analysis based on one-dimensional flow and integration issues are not yet visible, mixed internal and external compression will be used as it allows for a cowl that is parallel to the free stream flow. Before detailing the method of the compression system design, it should be noted that the compression system is important in the determination of the performance of the overall engine, as the airflow which exits the compression system feeds directly into the burner.

4.1 Boundary Conditions

The boundary conditions were taken as:

i)Pressure far field for inlet

ii) Pressure outlet for exit

iii) Wall for remaining boundaries

The initial conditions were given as:

i) Ambient temperature (271.06 K)

ii) Ambient pressure (0.95 bar)

iii) Speed of sound (330 m/s approx.)

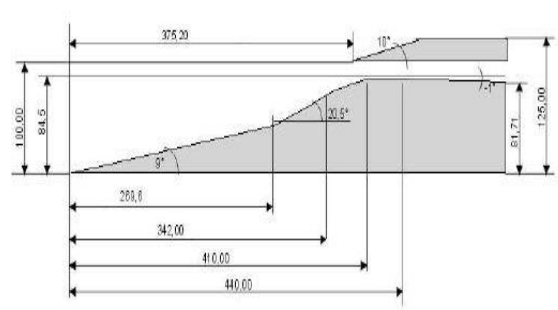

Figure 4. Scramjet inlet geometry

From the above standard inlet variable geometry arises. The cowl lip present in the inlet have a dimension of 375.20 mm. Variable geometry will have a forward movement of 355.20 mm instead of 375.20 mm (horizontal) and a downward movement of 95 mm instead of 100 mm (vertical).

5. Computational Results

For this computation the initial conditions were given as same as in the theoretical part. The following results were shown to prove the similarity between the computational and theoretical part.

5.1 Standard Inlet Results

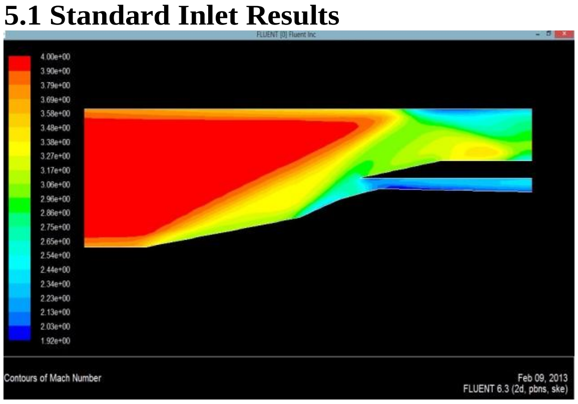

Figure 5. Mach contour for M_0=4

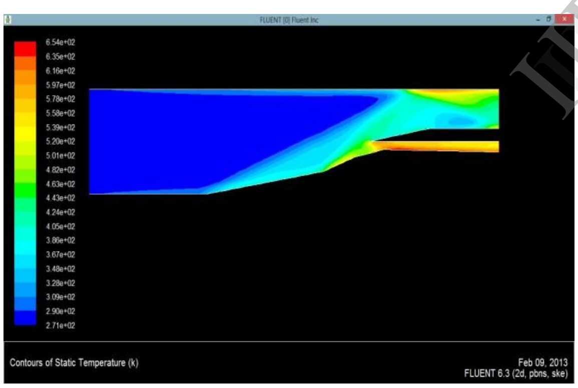

Figure 6. Temperature contour for M_0=4

From the above figure we can see the burner entry Mach number as 2.13 and burner entry temperature as 558K..

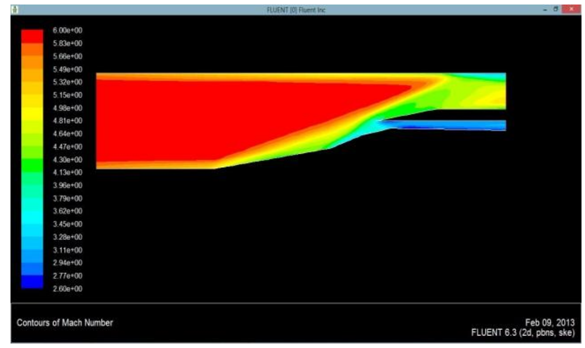

Figure 7. Mach contour for M_0=6

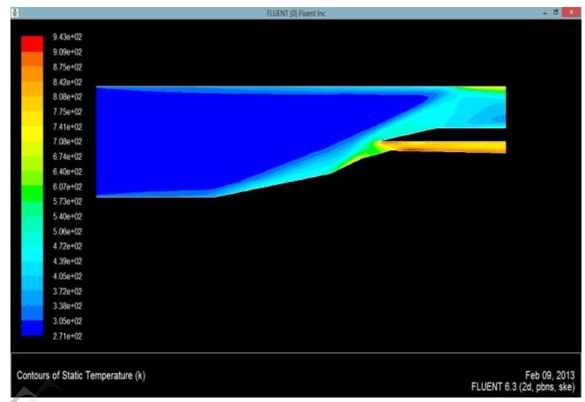

Figure 8. Temperature contour for M_0=6

From the above figure we can see the burner entry Mach number as 3.34 and burner entry temperature as 909K.

5.2 Results for Forward Movement Cowl Lip Geometry

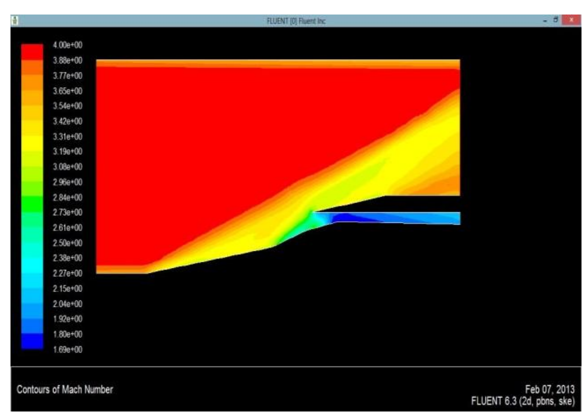

Figure 9. Mach contour for M_0=4

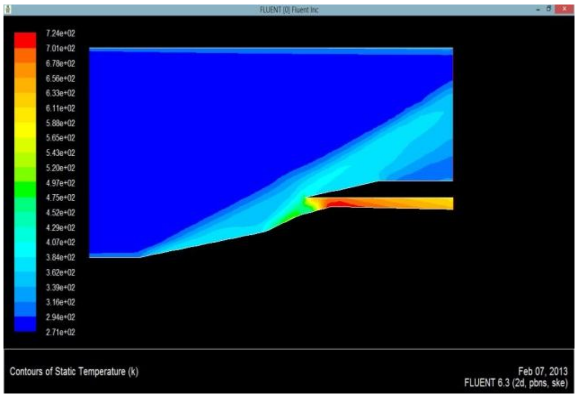

Figure 10. Temperature contour for M_0=4

From the above figure we can see the burner entry Mach number as 2.15 and burner entry temperature as 552K.

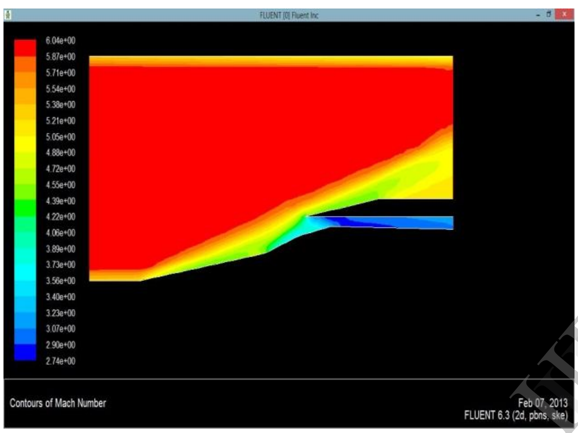

Figure 11. Mach contour for M_0=6

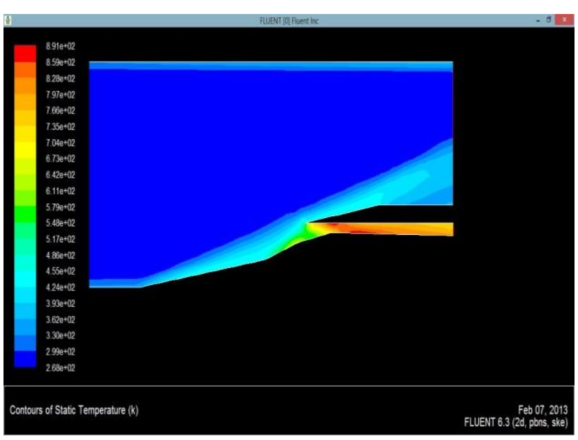

Figure 12. Temperature contour for M_0=6

From the above figure we can see the burner entry Mach number as 2.9 and burner entry temperature as 828K.

5.3 Results for Downward Movement Cowl Lip Geometry

The cowl lip present in the inlet have a dimension of 95 mm instead of 100 mm.(Vertical)

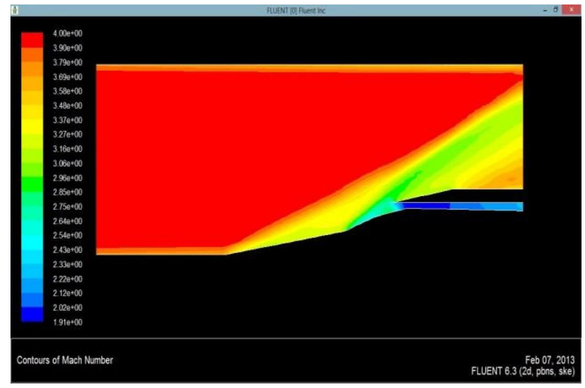

Figure 13. Mach contour for M_0=4

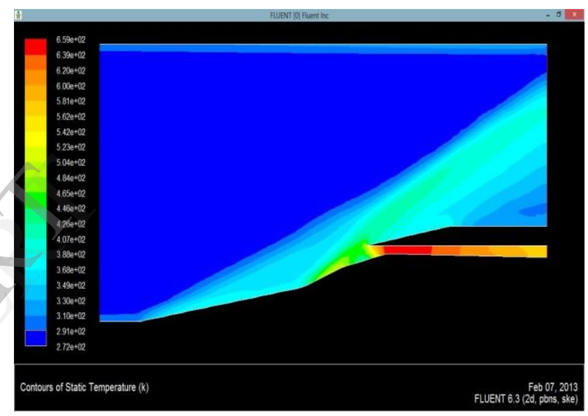

Figure 14. Temperature contour for M_0=4

From the above figure we can see the burner entry Mach number as 2.22 and burner entry temperature as 542K.

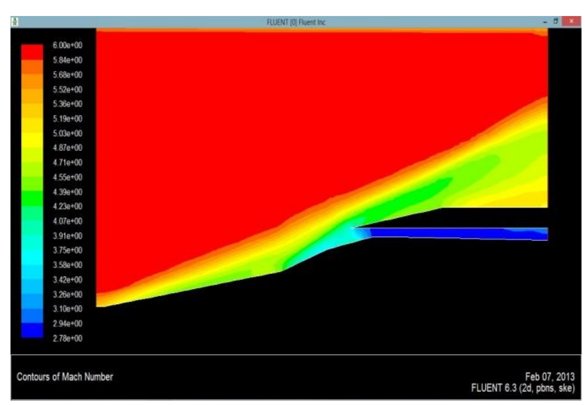

Figure 15. Mach contour for M_0=6

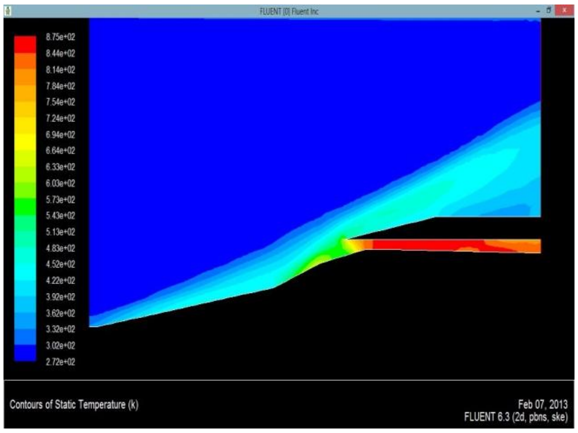

Figure 16. Temperature contour for M_0=6

From the above figure we can see the burner entry Mach number as 2.78 and burner entry temperature as 814K.

6. Conclusion

A comparison was made between theoretical part as well as with the computational part. There was also few tables to explain the similarities between them. The following were the tables with their values obtained by the two approaches.

Parameters at station 3	Theoretical	Computational
Mach number	2.47	2.77
Static Temperature (k)	948	909
T_3/T_0	3.49	3.35

Table 5. For M_O=6

Parameters at station 3	Theoretical	Computational
Mach number	2.39	2.13
Static Temperature (k)	519.89	558
T_3/T_0	1.92	2.05

Table 6. For M_O=4

6.1 Standard Inlet Results

PARAMETERS	M_O=4	M_O=5	M_O=6
M_3	2.3	2.7	2.94
T_3(K)	558	686	909

Table 7. Results of Standard Inlet

6.2 Forward Movement Inlet Results

PARAMETERS	M_O=4	M_O=5	M_O=6
M_3	2.15	2.58	2.9
T_3(K)	552	657	828

Table 8. Results of Forward Movement Inlet

Parameters at station 3	Theoretical	Computational
Mach number	2.39	2.15
Static Temperature (k)	519.89	552
T_3/T_0	1.92	2.37

Table 9. Results of Forward Movement Inlet for M_O=4

Parameters at station 3	Theoretical	Computational
Mach number	2.47	2.9
Static Temperature (k)	948	828
T_3/T_0	3.49	2.94

Table 10. Results of Forward Movement Inlet for M_O=6

6.3 Downward Movement Inlet Results

PARAMETERS	M_O=4	M_O=6	M_O=7
M_3	2.22	2.78	3.16
T_3(K)	542	814	983

Table 11. Results of Downward Movement Inlet

Parameters at station 3	Theoretical	Computational
Mach number	2.39	2.22
Static Temperature (k)	519.89	542
T_3/T_0	1.92	2.0

Table 12. Results of Downward Movement Inlet for M_O=4

Parameters at station 3	Theoretical	Computational
Mach number	2.47	2.78
Static Temperature (k)	948	844
T_3/T_0	3.49	3.11

Table 13. Results of Downward Movement Inlet for M_O=6

6.4 Comparison of Various Inlets

Parameters	Standard	Forward	Downward
M_3	2.3	2.15	2.22
T_3	558	552	542
T_3/T_0	2.05	2.03	2.0

Table 14. Comparison for various inlets at M_O=4

Parameters	Standard	Forward	Downward
M_3	2.7	2.58	2.6
T_3	686	657	652
T_3/T_0	2.53	2.42	2.40

Table 15. Comparison for various inlets at M_O=5

Parameters	Standard	Forward	Downward
M_3	2.94	2.9	2.78
T_3	875	828	814
T_3/T_0	3.22	3.05	3.00

Table 16. Comparison for various inlets at M_O=6

From the above tables we can able to understand that the vertical movement of cowl lip shows some better results. Cycle static temperature ratio (T_3/T_0) in case of vertical movement was better such that the burner entry temperature T_3 was optimum.

7. References

1. M. Krause, B. Reinartz, J. Ballmann, 2006,"Numerical Computations For Designing a Scramjet Intake", 25th International Congress of the Aeronautical Sciences.

2. Derek J. Dalle, Sean M. Torrez, and James F. Driscoll, 31 July - 03 August 2011, "Performance Analysis of Variable-Geometry Scramjet Inlets Using a Low-Order Model", 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, AIAA 2011-5756.

3. Birgit U. Reinartz, 2008, "Performance Analysis Of a 3D Scramjet Intake", 26th International Congress of the Aeronautical Sciences.

4. Scott D. Holland, March 1995, "Mach 10 Computational Study of a Three-Dimensional Scramjet Inlet Flow Field", NASA Technical Memorandum 4602.

5. Kristen Nicole Roberts, August 2008, "Analysis and Design of a Hypersonic Scramjet Engine with a Starting Mach Number of 4.00".

6. Scott D. Holland, January 1995, "Internal Aerodynamics of a Generic Three-Dimensional Scramjet Inlet at Mach 10", NASA Technical Paper 3476.

7. Heiser, William H., David T. Pratt, 1994, "Hypersonic Air breathing Propulsion" Washington, D.C.: American Institute of Aeronautics and Astronautics.