

Numerical Analysis of Ramjet Spike with Various Cone Angles

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Abstract - The main objective is to improve the efficiency of Ramjet Engine. The engine Inlet is of primary importance for all air-breathing propulsion engines. Its major function is to collect the atmospheric air at free stream Mach numbers, slow it down and to compress it efficiently. The geometries used are planar with different Mach numbers 2, 2.5, 3. The first inlet is modified and the oblique shock is produced at the edge of the spike. In the second inlet, a hole of .07874 inch is made at .5 inch length of the cone, the hole allows the inflow of oblique shock i.e. the oblique shock is absorbed through the holes, followed by normal shock which then expands behind the length of the cone thus increasing the mass flow rate for adequate combustion. The design and analysis of inlet spike is done in 2-D with the help of ANSYS software.

Keywords – Efficiency, Oblique shock, Normal shock, Spike, Cone Angle.

I. INTRODUCTION

Ramjet engine is the simplest of air-breathing engines consisting of an air-inlet, combustor and an exhaust nozzle. During the operation the atmospheric air flows continuously through these major components. The air-inlet convert the incoming air kinetic energy into pressure energy called ram pressure. The combustion chamber ignition and injection is followed by the high pressure air flowing from the spike which increases the air fuel mixture temperature to a higher value. The outcome of combustion are allowed to expand in the exhaust nozzle, the resultant velocity due to the expansion is far greater than that of the air entering the engine. The direction of the flight is determined by the thrust produced by the momentum of air after the combustion. Ram pressure is the phenomenon which plays an important role for thrust generation of engine at supersonic flight speeds. For flight speeds above Mach 2.5 or 3 the ratio of ram pressure becomes so high that no longer any turbo compressor are needed for the generation of efficient thrust. Indeed, the ratio of pressure eventually rises to a higher values that the associated with the higher increase of temperature due to Ram effect makes it impossible or difficult to place speed rotating machinery. The combination of these circumstances give rise to the Ram engine, in which the pressure increase is determinable only to the ram effect of

the high flight speed; no turbo machinery is involved and the afterburner is the main thrust producer. Ramjets are basically lightweight and simple power plants making them paradigmatic for the supersonic flight vehicles.

II. PROCEDURE

1. Governing Equations for shockwave theory:

a. Oblique shock theory relations:

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

b. Continuity equation in conservation form,

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{v} = 0 \quad \dots\dots\dots (2.1)$$

Continuity equation in non conservation form,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad \dots\dots\dots (2.2)$$

c. Momentum equation in non conservation form,

$$\rho \frac{Du}{Dt} = -\frac{\partial \rho}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \quad \dots\dots\dots (2.3)$$

Momentum equation in conservation form,

$$\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho u \vec{V}) = -\frac{\partial \rho}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \quad \dots\dots\dots (2.4)$$

d. Energy equation in non conservation form,

$$\rho \frac{D}{Dt} \left(e + \frac{V^2}{2} \right) = \rho \dot{q} - \frac{\partial (up)}{\partial x} - \frac{\partial (vp)}{\partial y} - \frac{\partial (wp)}{\partial z} + \rho \vec{f} \cdot \vec{V}. \quad \dots\dots\dots (2.5)$$

Energy equation in conservation form,

$$\rho \frac{\partial}{\partial t} \left[\left(e + \frac{V^2}{2} \right) \right] + \nabla \cdot \left[\rho \left(e + \frac{V^2}{2} \right) \vec{V} \right] = \rho \dot{q} - \frac{\partial (up)}{\partial x} - \frac{\partial (vp)}{\partial y} - \frac{\partial (wp)}{\partial z} + \rho \vec{f} \cdot \vec{V} \dots\dots\dots (2.6)$$

e. Equation of state,

$$P = \rho RT \quad \dots\dots\dots (2.7)$$

When the flow is slowed by viscous effects, the boundary layer loss in kinetic energy is obtained due to viscous dissipation. The interaction of shock layer with the boundary layer makes it fully viscous thereby altering the shape of shock wave and pressure distribution.

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

2. Relations for Prandtl-Mayer Expansion Theory:

Prandtl-Mayer Expansion wave is an alias to expansion wave. It consists of infinitesimal number of Mach waves. The flow angle θ , and flow variables like M and V is to be considered for the analysis of particular change.

$$v(M) = \sqrt{\frac{\gamma+1}{\gamma-1}} \arctan \sqrt{\frac{\gamma-1}{\gamma+1}} \arctan \sqrt{M^2 - 1} \quad \dots\dots\dots (2.8)$$

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

III. METHODOLOGY

Design of the Ramjet was an iterative process. Before the iterations could begin, a number of conical shock flow calculations were carried out. Pressure ratios, shock angles and area ratios were computed and the results are compiled. Under the methodology we are going to see about the design process, grid, mesh factors and required inlet boundary conditions.

a. Design:

The First priority was to choose an inlet cone angle to determine maximum total pressure recovery. The oblique shock wave produced on the lip of the cowling was used to determine the geometry of inlet, where the cone is placed at the centre of the body. Mach number for the combustion chamber was selected and the resulting cross-sectional area of the combustor was calculated. The necessary inlet area was determined by the calculation of cross section area for the combustion, which then evaluates the dimensions of the lip of inlet cowl. By giving these dimensions calculation for inlet air mass-flow rate was done and compared to the mass-flow rate input into Ansys FLUENT. The inlet was made larger, for the increase of more mass flow rate and the cone angle was adjusted thereby repeating the process again.

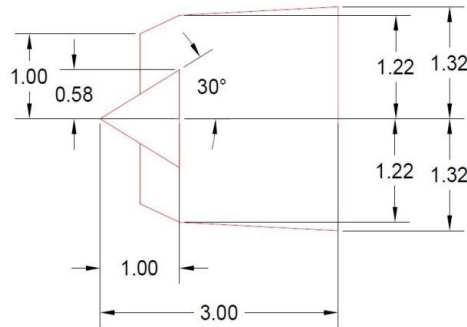


Fig 3.1: Design of cone angle 30°

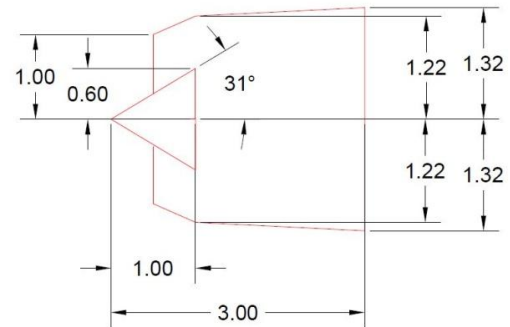


Fig 3.2: Design of cone angle 31°

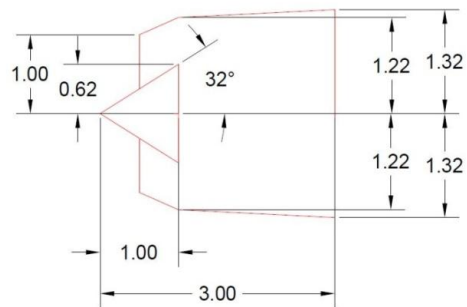


Fig 3.3: Design of cone angle 32°

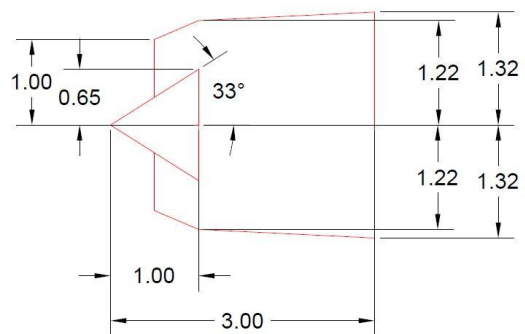


Fig 3.4: Design of cone angle 33°

Where all the dimensions of design are in inches.

b. Mass flow rate calculations:

$$\dot{m} = \frac{p}{RT} \times A(M\sqrt{\gamma RT}) \quad \dots\dots\dots 3.1$$

$$A = \frac{\pi}{4} \times (D^2 - d^2) \quad \dots\dots\dots 3.2$$

1. Model Calculations:

$$A = \frac{\pi}{4} \times (25.4^2 - 12.988^2)$$

$$\therefore A = 374.19 \text{ mm}^2$$

$$\dot{m} = \frac{101325}{287 \times 300} \times 374.19 (3\sqrt{1.4 \times 287 \times 300}) \quad \therefore \dot{m} = 4.58 \text{ kg/sec}$$

Table 3.1: Mass flow rate at various cone angles

(degree)	Mach number	Outer Diameter D(mm)	Inner diameter D(mm)	Mass flow rate $\dot{m}$ (kg/sec)
30°	2	25.4	11.54	3.28
	2.5	25.4	11.54	4.10
	3	25.4	11.54	4.92
31°	2	25.4	12.01	3.21
	2.5	25.4	12.01	4.01
	3	25.4	12.01	4.81
32°	2	25.4	12.49	3.13
	2.5	25.4	12.49	3.92
	3	25.4	12.49	4.70
33°	2	25.4	12.98	3.05
	2.5	25.4	12.98	3.82
	3	25.4	12.98	4.58

d. Mesh or grid:

A 2D grid was created based on the design geometry of the Ramjet. The grid fineness depends on the relative gradients of the flow. The grid fineness will be highest around at the inlet off all leading edges and along all the boundary layers within the ramjet design. Fig 3.1 shows a part of a representative grid used for both with and without hole.

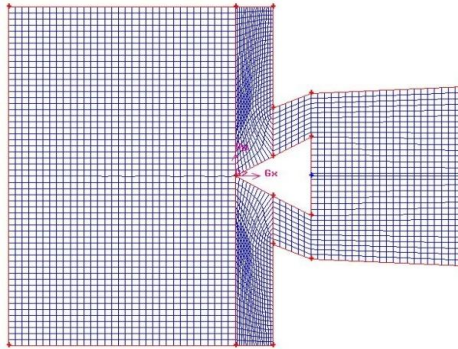


Fig 3.1: Mesh view of the design

e. *Boundary conditions*

In general the boundary condition given to the design of various cone angles subjected to different flow or different Mach number is:

Table 3.2: Boundary conditions for the inlet design

NAME	TYPE
fluid	Air
wall	Wall
V_{in}	Velocity-inlet
W	Wall
pout	Pressure-outlet
Default-interior	Interior

IV RESULTS AND DISCUSSIONS

The analytical results of cone angles 30° , 31° , 32° , 33° with different Mach numbers 2, 2.5 and 3 are found using Ansys Fluent for respective total Pressure Contours as indicated below.

a) Cone Angle 33°

I. Cone Angle 33° (Mach = 2)

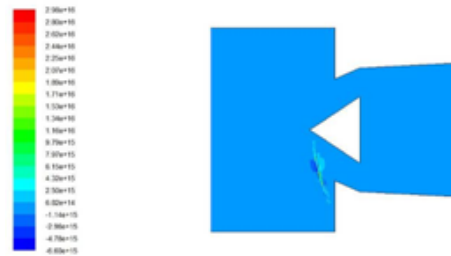


Fig 4.1: Total Pressure Contour (Mach = 2)

II. Cone Angle 33° (Mach = 2.5)

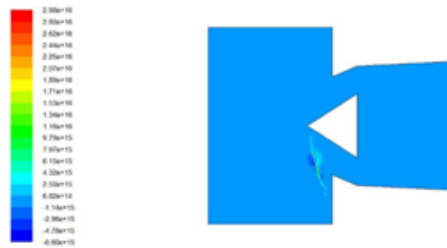


Fig 4.2: Total Pressure Contour (Mach = 2.5)

III. Cone Angle 33° (Mach = 3)

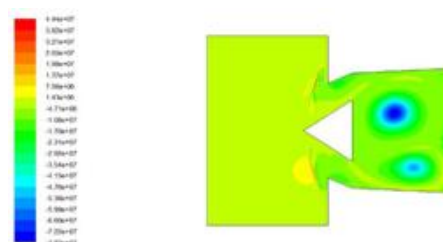


Fig 4.3: Total Pressure Contour (Mach = 3)

From the analysis the results of 33 degree cone at 0.5inch shows the better pressure recovery. To increase the mass flow rate a hole of 2mm is made at 0.5 inch length of

the cone and at 0.5 inch height of the cone. The hole allows the inflow of oblique shock i.e. the oblique shock is absorbed in through the hole, forming normal shock which then expands behind the length of the cone thus increasing the mass flow rate for combustion.

2. Model Calculations:

a. Mass flow rate with 0.07847 inch hole:

$$\dot{m} = \frac{p}{RT} \times A(M\sqrt{\gamma RT})$$

$$A = \frac{\pi}{4} \times (D^2 - d^2) + \frac{\pi}{4} \times (d^2 - d'^2)$$

$$= 503.26 \text{ mm}^2$$

$$\dot{m} = \frac{101325}{287 \times 300} \times 503.26 (3\sqrt{1.4 \times 287 \times 300})$$

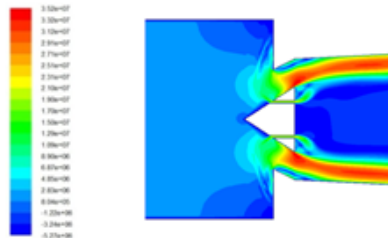
$$= 6.17 \text{ Kg/sec}$$

As we can see the mass flow rate increase due to introducing holes in spike, it will increase the combustion ratio however in practical basis many other force may counteract the mass flow rate.

a. Cone angle 33° for Mach 3 with holes in spike:



Fig 4.4: Total Pressure Contour (M = 3) with holes in spike

Fig 4.5: Velocity Contour ($M = 3$) with holes in spike

V. Maximum Pressure and Maximum Velocity by Various Cone Angles:

Each cone angles varying from 30° to 33° gave different readings about the maximum pressure and maximum velocity in accordance with the variation in Mach number is tabulated as follows:

Table 4.2: Maximum Pressure and Maximum Velocity values

Cone Angle(θ)	Mach Number	Maximum pressure (Pascal)	Maximum velocity (m/s)
30°	2	$2.94e^{+07}$	$5.14e^{+03}$
	2.5	$5.58e^{+07}$	$6.87e^{+03}$
	3	$8.97e^{+07}$	$9.21e^{+03}$
31°	2	$1.49e^{+07}$	$1.14e^{+03}$
	2.5	$7.53e^{+07}$	$1.24e^{+03}$
	3	$1.43e^{+08}$	$1.45e^{+04}$
32°	2	$9.49e^{+07}$	$1.04e^{+04}$
	2.5	$1.48e^{+08}$	$1.15e^{+04}$
	3	$2.39e^{+08}$	$1.23e^{+04}$
33°	2	$2.98e^{+08}$	$1.34e^{+04}$
	2.5	$3.38e^{+08}$	$1.50e^{+04}$
	3	$4.44e^{+08}$	$2.42e^{+04}$

VI. COMPARISION GRAPHS

The comparison graph plotted based on the Mach numbers which has the perfect graph co-ordination with respect to Total Pressure Recovery.

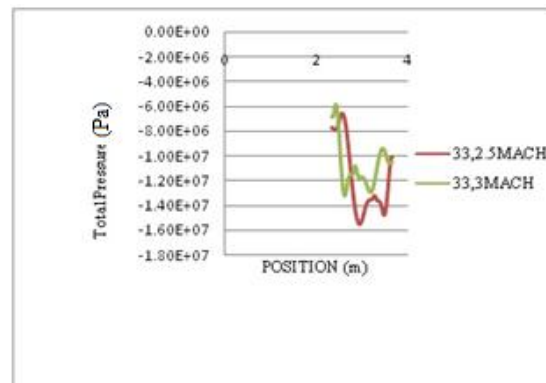


Fig 6.1: Comparison graph for Total Pressure of Cone Angle - 33°

VII. CONCLUSION

We would like to conclude this paper by saying that these are the cone angles which we have tried they are 30, 31, 32, & 33. For all these angles we have showed the mass flow rate calculations and best efficient cone angle graph, so we conclude by saying that the most efficient Cone Angle is 33° for Ramjet Engine as the mass flow rate that is more efficient, so we have made one more design for Cone Angle 33° by introducing two holes in Spike at 0.5 inch length of the cone so that the hole allows the inflow of oblique shock followed by normal shock and it increases the mass flow rate from 4.58 kg/sec to 6.17 kg/sec for better combustion. Thus we have designed and analyzed the inlet spike of the ramjet engine which helps to increase the mass flow rate and by decreasing the pressure loss with variations in cone angle and Mach number.

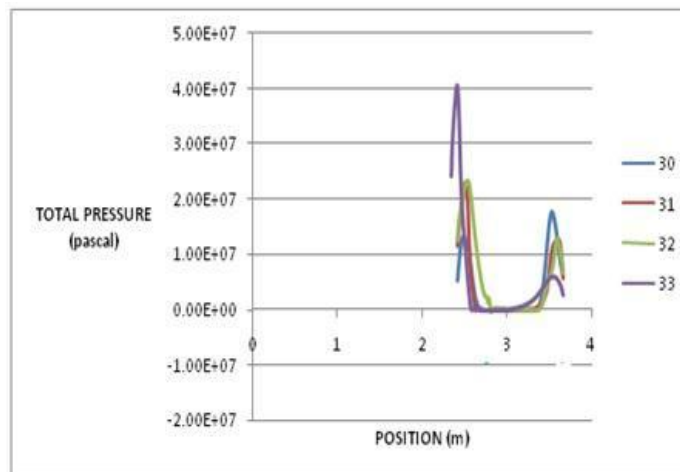


Fig 7.1: Comparison graph for Total Pressure of all cone angles

After plotting the graph for all the Cone angles together it can be seen that, the Cone angle 33° gives better value of Total Pressure Recovery compared to other Cone angles that we have analyzed.

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