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Performance Analysis of Scramjet Engine with Different Nozzle Angles

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ABSTRACT

The main objective of this project was, to design a scramjet engine and analyzing the exhaust nozzle using ANSYS fluent for various Mach number by using petrol as fuel and calculating the velocity at the exhaust of the engine. This engine contains a combustion chamber, fuel injector ignition system and also an exhaust nozzle but without an inlet convergent part instead it was given with the required supersonic flow directly. The supersonic flow was produced under the principle of isentropic flow such a way when air was been released at a pressure difference of less than 0.528. Ultimately the flow was supersonic which was ideally expanded through a supersonic nozzle to reduce shock waves and that was given as inlet to the scramjet engine thereby igniting the fuel and studying the thrust produced by the engine after combustion .In this work the supersonic flow for various conditions were completely analyzed using Mach number 2.28. Various things like the Mach loss exhaust expansion and the shock waves produced were analyzed for three different kinds of nozzle by having 10º exhaust angle, 12º exhaust angle and 15º exhaust angle. The results obtained after analysis provided the ideal nozzle for the use in this scramjet engine. Similarly, the experimental analysis has shown very good agreement with the numerical analysis which was performed in ANSYS.

Keywords- Isentropic flow, Nozzle Scramjet, Mach Number.

1. INTRODUCTION

A ramjet is a jet engine, works under the ram effect which is the compressing effect obtained by locating the entrance to an air-intake duct in the air stream. By the way to take advantage of the relative velocity between the air intake and the air stream by increasing the static pressure in the system to aid in compressing the charge air or to maintain the flow of air through a cooling system. However, ramjet engine is a form of air breathing jet engine that uses the engine's forward motion to compress incoming air without an axial compressor. The ramjet engine is a simple one which has no moving parts. The intake air is then slowed from a high subsonic or supersonic speed to a low subsonic speed by aerodynamic diffusion created by the inlet and diffuser. Following this, the fuel is injected into the combustion chamber where combustion takes place at constant pressure.

The expansion of hot gases accelerates the subsonic exhaust air to a supersonic speed, which has been passed on the exhaust nozzle thus the way which gives the result in a forward velocity. From the literature survey it is observed that, ramjets work most efficiently at supersonic speeds around Mach 3. A scramjet (supersonic combusting ramjet) which is an advancement of a ramjet engine in which combustion takes place in supersonic air flow. Scramjet operates on high vehicle speed to forcefully compress the incoming air before combustion, whereas in a ramjet engine the air is decelerated to subsonic velocity before combustion while airflow in a scramjet is supersonic throughout the entire engine. Scramjet also decelerates the velocity of incoming air through the compression, but still it remains at supersonic speed, it is not brought down to subsonic as in the ramjet engine. This creates a very less drag force in scramjet engine when operating at very high velocity by making the scramjet more efficient than a ramjet in higher velocity.

The scramjet engine has the following parts namely an inlet nozzle, a fuel injector, a combustion chamber, an ignition system and an exhaust nozzle. In addition to that, some of the engines have a flame holder to maintain continues combustion in order to foresee the various factors like shock waves that might lessen combustion or even the supersonic velocity of the fluid. In this study, the inlet nozzle has been designed in such a way to reduce the shock wave that would automatically accelerate combustion chamber [1]. The fuel is injected quite some distance before the combustion chamber and some gap is maintained between them to cause the good mixture of air and the fuel, because it is necessary to produce complete combustion of the fuel. Besides some other type of scramjet engine has a different set up in which the fuel injector and the ignition would be next to each other inside the combustion chamber and the length of the chamber would be a long enough to make it suitable for the complete combustion of the fuel, then at that state the Mach number or the velocity would not be as high as required, vice versa the increase of kinetic energy leads to the decrease of stagnation pressure [2]. Similarly the pressure energy is then converted into kinetic energy using an exhaust nozzle thereby producing the axial thrust. The thrust to weight ratio of a scramjet engine is very low when it is compared to that of a rocket engine, but still more pay load can be taken because of, the absence of the on-board oxidizer which will be present in rocket engine, but not in a scramjet engine because it being an air breathing engine.

2. METHODOLOGY

The required supersonic flow, to start the scramjet is achieved by the application of isentropic flow process. In which, the air is released from high pressure to low pressure at a ratio of less than 0.528 mach no, the flow shows as supersonic. The complete expansion is achieved by using a supersonic nozzle. In this project we stored air at 120 to 150 psi in an air tank and the outlet diameter is maintained as 1.90cm, then the out let pipe is given as inlet for the scramjet engine which is similar to that of the outlet diameter. Some modifications have been made to the supersonic outlet pipe; it is placed in such a way, so that the subsonic air will flow around it causing a pressure drop at the outlet, which will further reduce the pressure ratio causing the inlet Mach number to increase slight high, in turn this gains higher Mach number with less effort [3-5]. For the scramjet engine it is not with an inlet convergent part since it is already provided with a completely expanded supersonic flow.

A long narrow tube is followed by the combustion chamber in front of the spear, that is followed by the fuel injector and the spark plug, the backside of the spear acts as an flame holder preventing the flame away from supersonic flow such a way it position next to the expansion nozzle, which converts the pressure energy into velocity to produce axial thrust. The working of the engine is similar to that of a normal engine that is the inlet supersonic flow which decelerates in a smaller way in the spear, but still remains in supersonic, following that it successively originates the fuel injection and ignition, which increases the mass and the stagnation pressure after the combustion chamber increases exponentially thus the way the pressure is being converted into kinetic energy adversely it thereby produces the thrust for the engine. In this experiment two Mach number is been analyzed using Raleigh flow and Isentropic flow equation [6-8].

3. DESIGN OF THE SCRAMJET ENGINE

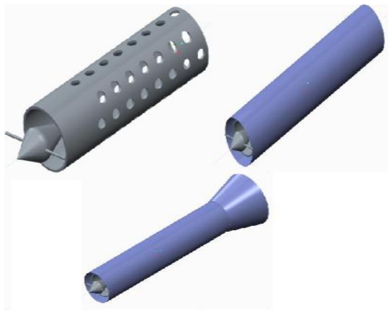

Fig.1 Combustion chamber with divergent exhaust

Fig. 2 Prototype model of scram jet engine before and after Combustion

4. GEOMETRIC PROPERTIES

Property	Dimension
Nozzle outlet diameter (cm)	**6**
Length of Engine (cm)	**50**
Combustion chamber diameter (cm)	**3.81**

5. BOUNDARY CONDITIONS

Table Boundary Conditions	Values
Inlet Stagnation Pressure (gauge)	827371Pa
Inlet Static Pressure (gauge)	127100 Pa
Inlet Total Temperature	477.8 K
Outlet Pressure (gauge)	96526.6 Pa

6. ANALYSIS

6.1. Modeling the Nozzle

The geometry of the nozzle was created using the design modeler of Ansys fluent. A 2D ax symmetric model of the exhaust nozzle was designed. Three different models were created with different angles, which were 10, 12 and 15 degrees. Hence, each model was used in order to find out the types of expansion like complete expansion, under expansion and over expansion. While, the nozzle consists of two regions, namely the expanding region and exhaust region, to find out the propagation of shocks. Each area was separated and updated for meshing.

6.2. Meshing

In this course of research, the ANSYS FLUENT was used, which comprises of triangular, quadrilateral cells or a combination of the two in 2D, tetrahedral, hexahedral, polyhedral, pyramid, or wedge cells or a combination of these in 3D. The choice of type of mesh purely based on the needs of your application. Since this work completely depends on the 2D ax symmetric model, we have chosen it between triangular or quadrilateral cell. Following this, meshing of the geometry was done by using the quadrilateral cell, then the geometry was meshed using face mesh which was the part of the structural mesh. Each and every face was meshed separately. After the sizing was done, proximity and curvature tools were used as an advanced size function, then the maximum and minimum size were given accordingly.

The plane thickness was maintained at zero millimeter. Following this, the number of division feature concept was used to obtain a much finer and dense mesh for the better results. In the number of divisional feature, the bias factor was given because in order to avail more elements near the boundary layer. The number of division was given to the inlet, boundary, outlet and the axis. At the inlet, the number of divisions were given as 75. Whereas at the outlet the number was 100. The number of divisions at the boundary was given in between the range of 50 and 100 accordingly. After the completion of meshing, the mesh quality such as element quality, aspect ratio, skewness and orthogonal quality was assessed completely.

It was said that the skewness was an appropriate indicator of the mesh quality and suitability. A skewness with value 0 was the best possible one and a skewness of 1 was almost never preferred. In this project the skewness was maintained as closer to the value of zero.

It was said that the aspect ratio was the ratio of longest to the shortest side in a cell. Theoretically it should be equal to 1 to ensure best results in order to get a precise value. For multidimensional flow, it was said categorically in several studies, the value of aspect ratio as nearer to one. Also it was found that, local variations in cell size should be minimal, i.e. adjacent cell sizes should not vary by more than 20%. Having a large aspect ratio can result in an interpolation error of unacceptable magnitude. In 2D, flipping and smoothing were the powerful tools for converting a poor mesh into a good mesh. Flipping involves combining two triangles to form a quadrilateral, then splitting the quadrilateral in the other direction to produce two new triangles. Flipping is used to improve quality measures of a triangle such as skewness. Mesh smoothing enhances element shapes and overall mesh quality by adjusting the location of mesh vertices. In mesh smoothing, core features such as non-zero pattern of the linear system are preserved as the topology of the mesh remains invariant. Laplacian smoothing is the most commonly used smoothing technique.

6.3. Boundary Conditions Used

Accordingly, the geometry of the nozzle it was divided into two zones, as mentioned earlier, boundary conditions given to these were: The inlet, the nozzle wall, axis, the exhaust, far field. The density-based analysis was done and the energy equation kept on. For this analysis, we used k-epsilon turbulent model which was compressible as well. For fluid the ideal gas was used and for viscosity the Sutherland model was selected which was a very accurate model. The inlet was given as pressure inlet and the calculated pressure value was given and the outlet was also given as the pressure inlet which provided with the atmospheric pressure. After that the operating conditions were set to zero, since we were using the gauge pressure in this study, instead of the absolute pressure.

6.4. Solving

Now for the solution method flow, the chosen modules were as follows, Turbulent Kinetic Energy and the turbulent dissipation rate, everything was set to second order upwind. The initialization was done from pressure inlet. The calculation was run 4500 iteration. From the above nozzle image, it can be clearly seen that there was no ideal expansion and the gases out of the exhaust was not the required velocity. This happened due to the shockwave and this can be reduced by increasing the nozzles diverging angle, here the graph between the density and the position in the various parts of the nozzle was provided. Since it was expanding through a nozzle, vice versa the density decreases while the area increases. This happens because the engine was a closed system and the combusted gases were expanding through the exhaust nozzle. But the decrease in density was not a gradual though the area increases gradually, air expands isentropically after combustion into the atmosphere the pressure drops at all the parts of the nozzle. But here the pressure drop was found to be instantaneous by the way it creates the shock waves across the entire lobe. From the below figure 3, we can clearly observe that there were appreciable variations in velocity profile that led to the conclusion that the velocity distributions across the entire section were not ideal.

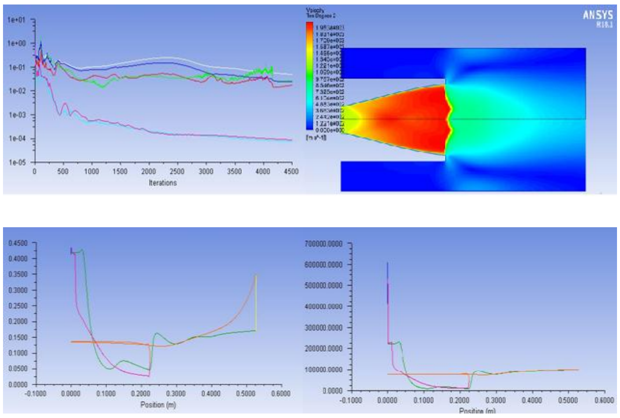

Fig. 3 - 10 degree – nozzle, density, pressure, velocity.

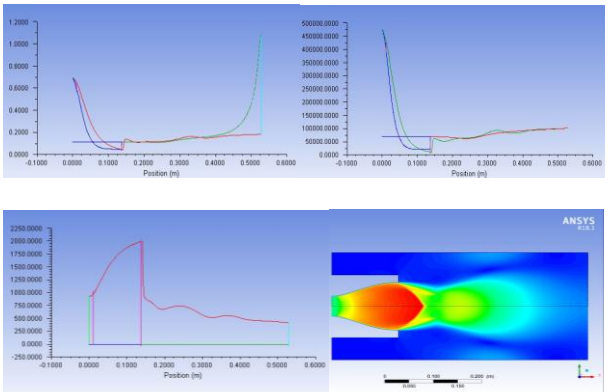

Fig. 4 - 12 degree – nozzle, density, pressure, velocity.

Here it can be seen that the gases are expanding ideally without any shock waves. Providing an ideal expansion and thereby creating thrust. This case was not like that of the previous nozzle. Here it was observed that the density was decreasing gradually, and the curve was found to be smooth. The pressure was decreasing gradually meaning that there was less chance for a shock wave to occur during expansion. In this figure 4, the obtained velocity profile was made, by plotting between the velocity and the position in the nozzle; it clearly provides a profile similar to that of the nozzle. This means that the gas velocity was increasing along with the nozzle.

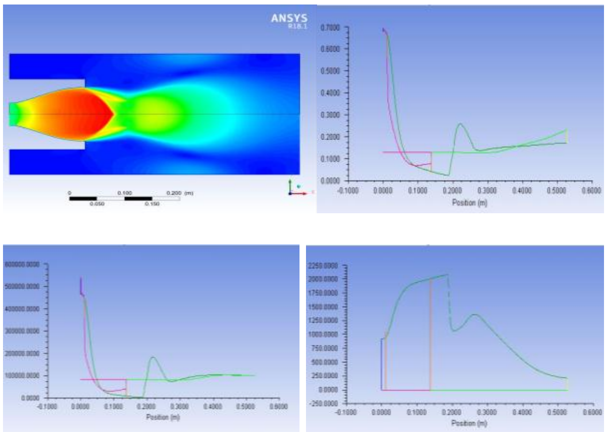

Fig. 5 - 15 degree – nozzle, density, pressure, velocity.

This figure 5 shows that, the nozzle was proving a type of expansion which was not ideal at the same time was also not under expansion. This nozzle may be useful and can produce thrust but there could be a chance for the gases to get chocked at the exhaust, thereby not producing much thrust. But it looks like for this scramjet engine this kind of nozzle might be useful one. Similar to the 12 degree nozzle the density was decreasing gradually, which states that the nozzle was expanding the gases properly. In this figure 5, the pressure was found to be decreases gradually. The above said figure clear that, the nozzle profile, which means that there was an increase in velocity as the area of the nozzle increases since it was an isentropic flow. Where the velocity increases as the area increases when the Mach number was greater than 1, it proves that, the flow was supersonic.

7. CONCLUSION

It has been calculated that, the thrust value was 2 kN, while the actual thrust was 0.5 kN calculated using load cell at Mach number of 2.27. As a result of this analysis, it is found that the nozzles having divergent angle of 12 deg and 15 deg is best suitable for the scramjet engine, since the 10 deg nozzle was creating shockwaves. Though the expansion was not ideal in 15 and 12 deg nozzle, it provides exhaust mach number greater than 3. Even though the expansion was not ideal in the 15 deg nozzle it becomes the default choice since it is producing the considerable amount of thrust. The efficiency increases as the Mach number increases so the scram jet engine is assisted with a first stage rocket engine to work it in hypersonic speed. It has been observed that the scramjet could attain a top speed of about Mach 12 to Mach 24. The efficiency is more since the velocity of the air is remains supersonic throughout the scam jet.

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