CFD Analysis of Single Cavity with Varying Front Ramp Angles and L/D Ratio of a Hypersonic Scramjet Combustion Engine

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***Abstract* - From the development of X-43, a hypersonic combustion engine recorded a speed of 10500km/hr, Supersonic Combustion Ramjet (SCRAMJET) engine has been recognized as the most promising air breathing propulsion system for the hypersonic flight condition. Mixing, ignition and flame holding in combustor are the critical challenges in the development of scramjet engine. Among all common methods used as the flame holding mechanism of hypersonic vehicle, the research of cavity flame holder has drawn an increasing scrutiny of many researchers, in which the re-circulation region formed inside the cavity for better flame-stabilization and fuel-air mixing process that proves to be the better performance method. In the present paper, the analyses are carried out with varying L/D ratio 5 & 10 and front ramp angle under single cavity configuration in order to determine better configuration in generating re-circulation region and flame holding capabilities. The models have been designed in ANSYS Design Modeler. Numerical simulations were done in ANSYS FLUENT using two-dimensional density based energy equation with k-epsilon turbulence model under standard non-equilibrium wall condition. Finally, the contours of static pressure, static temperature, turbulence kinetic energy, total pressure, x-velocity and mach number are taken and hence graphs have been plotted for better perception. . Among all the four models, it has been proved that single cavity with 15° front ramp angle L/D ratio 5 shows better performance in flame stabilization and vortex formation.**

***Index Terms* – Scramjet, supersonic combustion, flame-stabilization, cavity.**

I. INTRODUCTION

In 1947, Chackyeager developed Bell X-1, first manned aircraft to shatter the speed of sound that attained a supersonic speed of 1130km/hr (M-1.06) through a rocket powered plane. From then, researchers have shown a special interest towards the development of fast moving engines (M>5) and hence hypersonic vehicle plays a major role in areas such as orbital mission, re-entry projects which can be achieved by the scramjet engine. A scramjet engine is the direct descendant of a ramjet engine where it consists of air-inlet, combustion chamber with fuel inlet and an exhaust system. The performance of a hypersonic vehicle has an impact on maintaining a supersonic condition in the combustor. A simple outline of a scramjet engine is shown in figure-1.

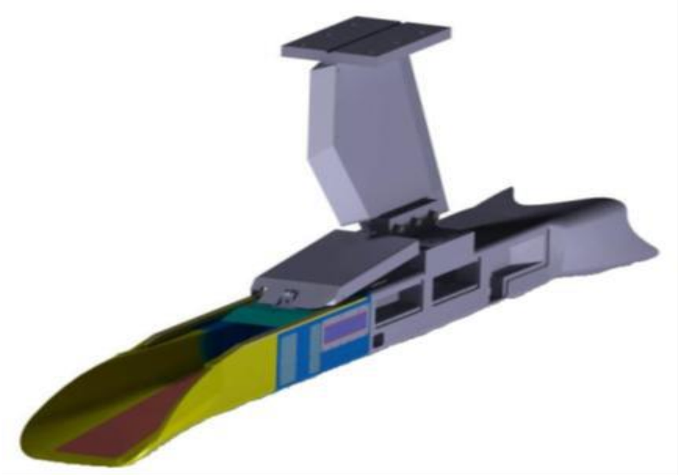

Fig-1 Outline of a Scramjet Engine
COURTESY: K.M Pandey, Gautam Choubey

Scramjets are designed to operate at hypersonic flight engines. The main criterion that causes problem to attain proper fuel-air mixing, ignition and flame holding in the combustor has to be vanquished. The most commonly preferred cavity flame holder method has been considered as the flame holding mechanism for hypersonic vehicle. Cavity flame holders were designed by the Central Institution of Aviation Motors (CIAM) in Moscow and are used for the first time in a joint Russian/French dual-mode scramjet flight test.

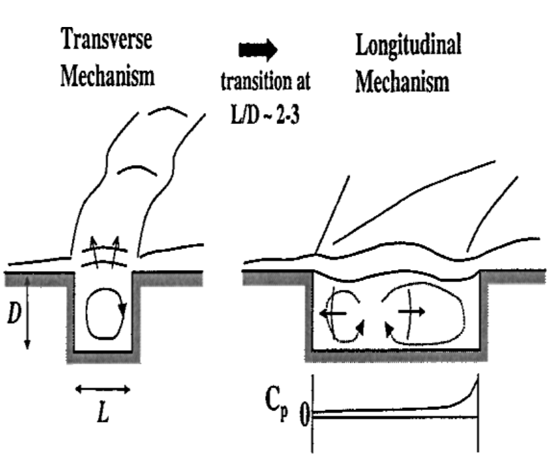

Fig-2 Open cavity L/D < 7-10
COURTESY: Kyung Moo Kim &co

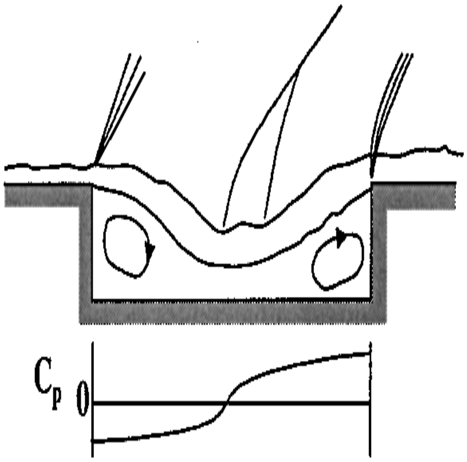

Fig-3 Closed Cavity L/D > 10-13
COURTESY: Kyung Moo Kim &co

A cavity exposed to a hypersonic flow experiences self-sustained oscillations, which leads to fluctuating pressures, temperature and velocities in and around the cavity. In tradition, cavity can be classified into two basic flow regimes that rely mainly on the length-to-depth ratio. From figure-2 above, the cavity has been termed as open, since the upper shear layer reattaches to the back face. The high pressure at the rear face as a result of the shear layer impingement increases the drag of the cavity. From the figure-3 above, the cavity has been termed as closed, since the free shear layer reattaches to the lower wall. The pressure increase in the back wall region and decrease in the front wall region results in large drag losses.

II. Literature Review

An exhaustive literature survey has been made regarding cavity flame holder. Researchers have shown distinctive heed towards the numerical assessment of cavity flame holder method in scramjets. K.M Pandey, Gautam Choubey[1] summarized hypersonic combustion of a scramjet combustor with a central lobed strut injector at flight mach number 7 and discovered that the inlet instabilities can be avoided by the increase in area of divergent combustor. Dingwu Zhanga and Qiang Wanga[2] summarized supersonic combustor cavities with front ramp angles of 15°,30°,-15°,-30° and discovered that the mixing effects have shown significant enhancement when the ramp angle is positive. As a conclusion, cavity with 15° front ramp angle showed the best performance since the large ramp angle added resistance and depletion of total pressure recovery. Jeevan Rao, Bhargav, Krupakar Pasala and Srinivasa Rao[3] has done a numerical simulation of viscous flow scramjet model at a mach 4 condition and analysed a hydrogen combustion process to predict the shock wave interaction in the upstream and downstream of their model. Krishnendu Sinha[4] in his paper concluded the shockwave formation and the phenomenon of shockwave reflection in an hypersonic flow for both scramjet and re-entry capsule which were studied practically and verified in practical manner. Meysam Mohammadi-Amin and Seyed Amir Hosseini[5] summarized the hypersonic inflatable aerodynamic decelerator concept and observed that this concept will improve the aerodynamic drag and heat load on the re-entry capsule. Vadim Yu, Aleksandrov Alexander.N, Prokhorov Vyacheslav.L, Semenov[6] summarized the development of hypersonic technology and they have discovered combustion occurs only near the wall due to the minor penetration of fuel into the supersonic flow, thus resulted in considerable losses in total pressure. B. Reinartz, J. Ballmann, L. Brown, Ch. Fischer and R. Boyce[7] has investigated the physical changes of elevated temperature on the flow field and compared both the shock-tunnel experiment with the CFD simulation result and that indicated the ratio of separation wall temperature to total temperature. The main objective of the present paper is to conduct analyses on single cavity with front ramp angle 0° & 15° under hypersonic flow and hence to compare the outcome for the discernment of better performance.

III. Methodology

The hypersonic flow characteristics and flow properties inside the scramjet engine was studied. The models were designed in ANSYS Design Modeler. Then, the model has been meshed with quadrilateral mesh property using ANSYS Mesh. Finally the analyses are carried out on ANSYS FLUENT 14.5 using two-dimensional density based Navier-Stroke energy equation with implicit solver method. Hence the results such as Static Pressure, Static Temperature, Turbulence Kinetic Energy, Total Pressure, Mach number, X-Velocity contours are obtained and correlation made to interpret the better performance and efficient model.

IV. Numerical Analysis

Geometry

Table-1

Model	1	2	3	4
Type	Single	Single	Single	Single

L/D ratio	5	10	5	10
Length of cavity (mm)	100	200	100	200
Inlet (mm)	122	122	122	122
Length of combustor (mm)	1550	1550	1550	1550
Front ramp angle	0°	0°	15°	15°

The configurations of various models that are designed in ANSYS Design Modeler are as shown in Table-1.

Meshing

The above four models are meshed using ANSYS Mesh. Quadrilateral mesh property has been chosen since the convergence time for analysis will be expeditious and accurate as compared to other meshing methods. Fine meshing were done near the cavity region using sizing property for the determination of accurate result in the combustion region.

Boundary Condition

For better analysis of model, boundary condition plays a vital role. Pressure far-field and pressure outlet are chosen as inlet and outlet boundary conditions respectively, at a Mach number 7 inside the model. The wall is made stationary with no-slip condition.

V. Results And Discussion

The analyses were carried out in ANSYS FLUENT 14.5. The two-dimensional models are analyzed using implicit method with all residual in first order upwind. Results are obtained only after all the residual is converged and possess a steady state condition. Finally the parameters such as static pressure, static temperature, turbulence kinetic energy, total pressure, Mach no, x-velocity are obtained and correlations are done as follows.

1. Single cavity with no front ramp angle and L/D ratio 5

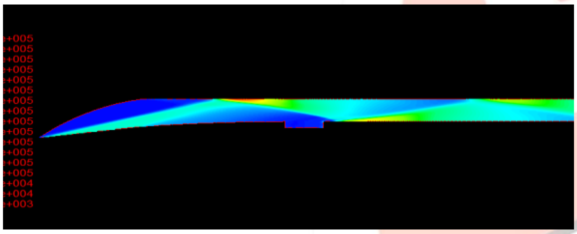

Fig-4 Contour of static pressure

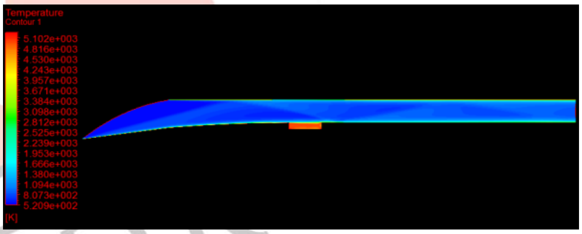

Fig-5 contour of static temperature

Fig-6 contour of turbulence kinetic energy

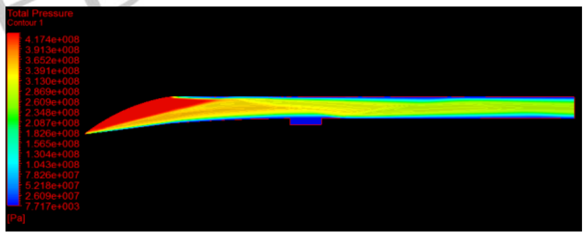

Fig-7 contour of total pressure

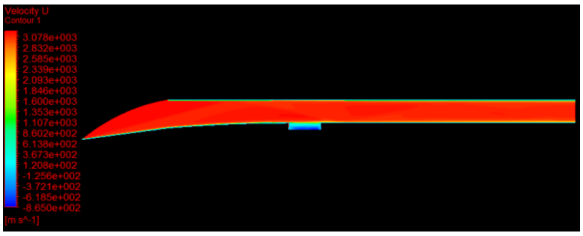

Fig-8 contour of x-velocity

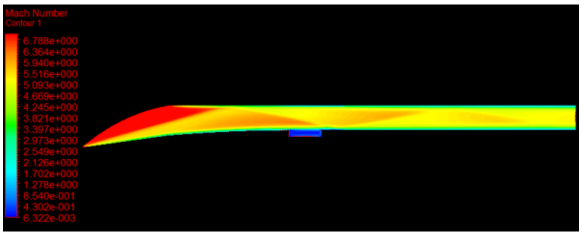

Fig-9 contour of mach no

The figures listed above are the contours obtained by the model 1. Fig 4 represents the contour of static pressure that demonstrates shock wave formation and the reflection of the shock waves. A maximum value of 755 KPa pressure rise has been found near the end of the wall in the shock reflection region. Figure-5 represents the contour of static temperature which indicates a high temperature rise inside the cavity region with a maximum value of 5245.57K. This proves that flame stabilization can be achieved inside the cavity. Figure-6 represents the contour of turbulence kinetic energy where the turbulence values of 368637J/kg has reached inside the cavity that proves proper mixing of air-fuel mixture in the cavity. Figure-7 represents the contour of total pressure where a value of 77KPa inside the cavity and maximum value of 4.30e8KPa are achieved at the shock formation region. Figure-8 represents the contour of x-velocity that denotes a minimum value of -864.988m/s inside the cavity due to the vortex formation. Figure-9 represents the contour of mach number that acquires a minimum value of 1.2 mach which proves combustion process will occur in supersonic condition for high thrust production.

2. Single cavity with no front ramp angle and L/D ratio 10

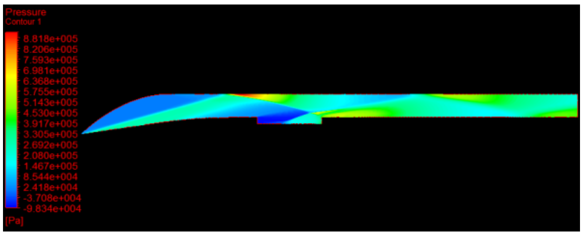

Fig-10 contour of static pressure

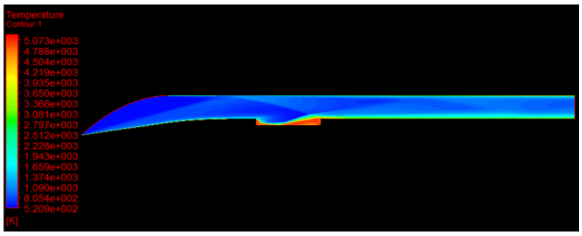

Fig-11 contour of static temperature

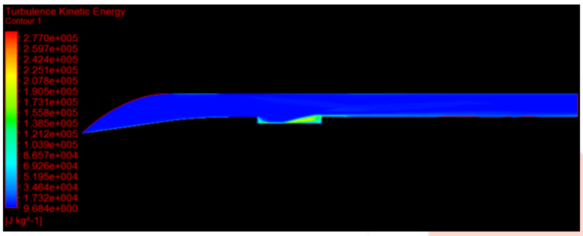

Fig-12 contour of turbulence kinetic energy

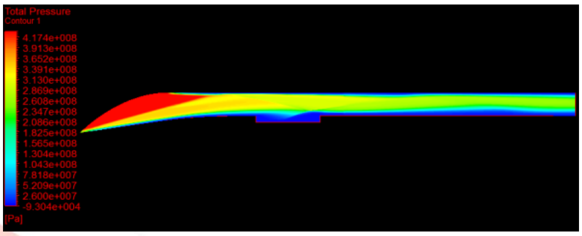

Fig-13 contour of total pressure

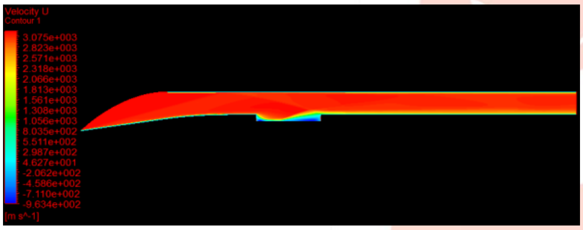

Fig-14 Contour of x-velocity

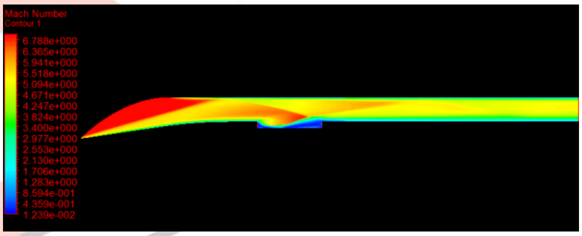

Fig-15 contour of mach no

The figures listed above are the contours obtained by the model 2. Figure-10 represents the contour of static pressure that demonstrates the shock wave formation at the downstream of the cavity where reflection of the shock waves also occurs. Here, a maximum value of 912KPa pressure rise has been found near the boundary of the wall. Figure-11 represents the contour of static temperature that indicates a maximum value of 5215.12K inside the cavity and hence states that flames stabilization can be achieved. Figure-12 represents the contour of turbulence kinetic energy where the turbulence value of 285672J/kg has attained inside the cavity that describes a vortex formation inside the cavity where a proper mixing of air-fuel mixture can be achieved. Figure-13 represents the contour of total pressure that shows a maximum value of 4.30e8KPa at the shock generating region. Figure-14 represents the contour of x-velocity where a minimum value of -963.43m/s has been achieved inside the cavity due to recirculation. Figure-15 represents the contour of mach number where a minimum value of 1.9 mach obtained near the cavity region for the benefit of supersonic combustion process.

3. Single cavity with 15° front ramp angle and L/D ratio 5

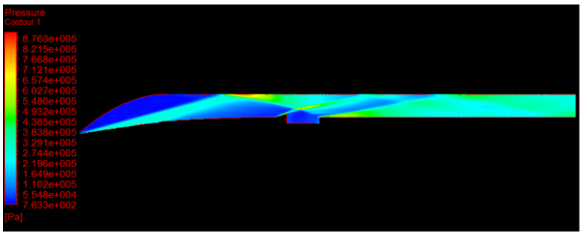

Fig-16 contour of static pressure

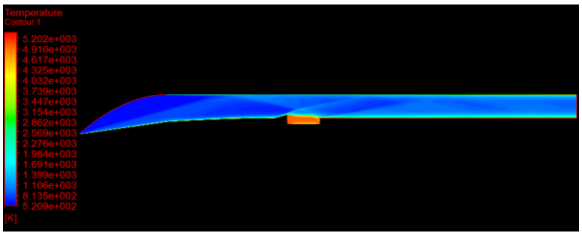

Fig-17 contour of static temperature

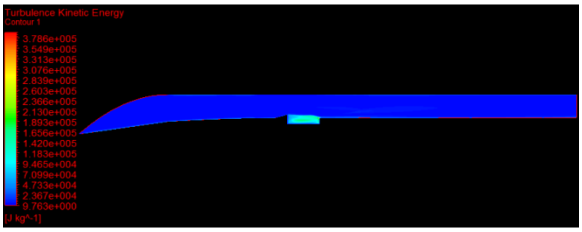

Fig-18 contour of turbulence kinetic energy

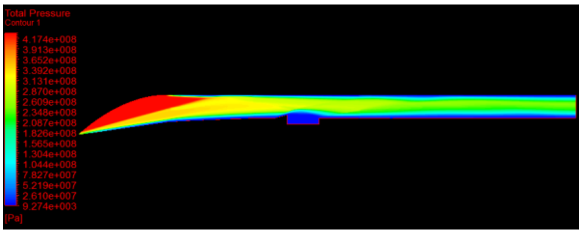

Fig-19 contour of total pressure

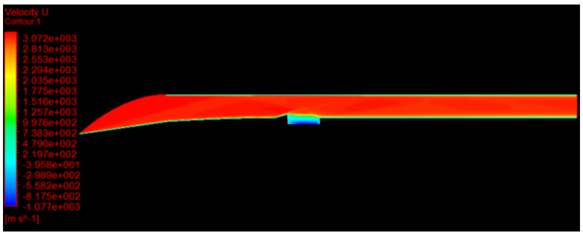

Fig-20 contour of x-velocity

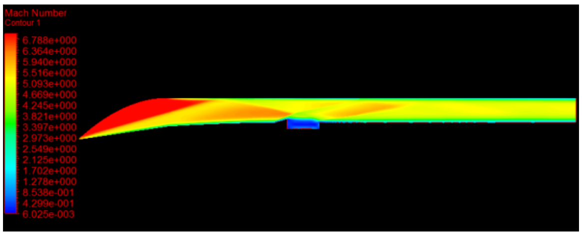

Fig-21 contour of mach no

The figures listed above are the contours obtained by the model 3. Figure-16 represents the contour of static pressure that demonstrates the shock wave formation at the upstream of the cavity due to the presence of front ramp angle and reflection of the shock waves occurs at the downstream of the cavity. Here, a maximum value of 903KPa pressure rise is found along the wall in shock formation region. Figure-17 represents the contour of static temperature which clearly shows a maximum value of 5348.67K inside the cavity for better flames stabilization. Figure-18 represents the contour of turbulence kinetic energy where the turbulence maximum value of 390408J/kg has been obtained in the cavity due to the vortex formation and proper mixing of air-fuel mixture. Figure-19 represents the contour of total pressure that denotes a minimum value of 92KPa inside the cavity and a maximum value of 4.30e8KPa at the shock formation region have been achieved. Figure-20 represents the contour of x-velocity where a minimum value of -1076.75m/s is achieved due to vortex formation inside the cavity. Figure-21 represents the contour of mach number that shows a minimum value of 1.3 mach in the supersonic combustion region inside the cavity.

4. Single cavity with 15° front ramp angle and L/D ratio 10

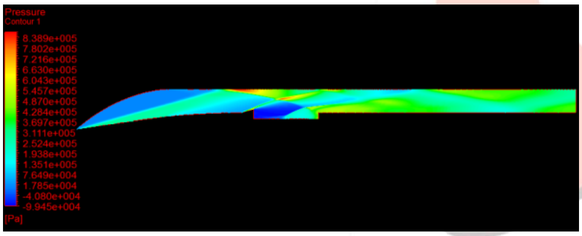

Fig-22 contour of static pressure

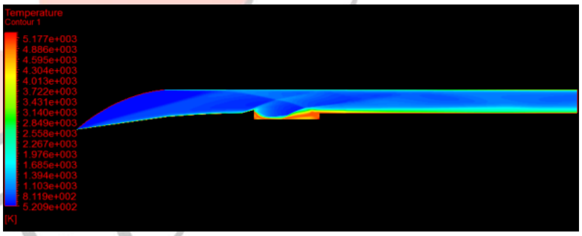

Fig-23 contour of static temperature

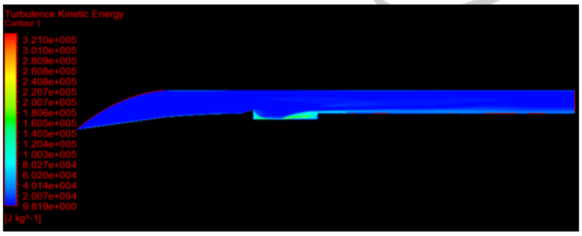

Fig-24 contour of turbulence kinetic energy

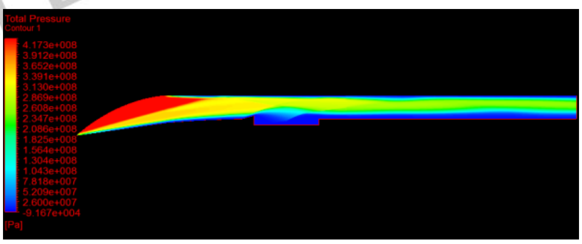

Fig-25 contour of total pressure

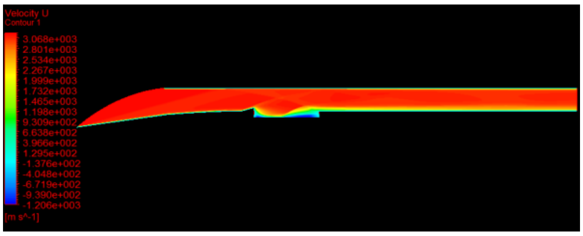

Fig-26 Contour of x-velocity

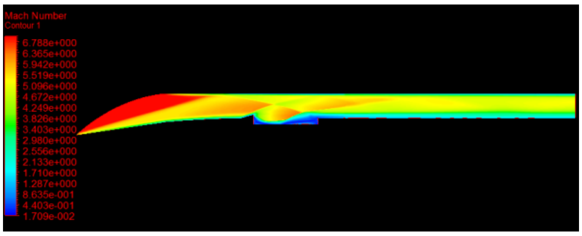

Fig-27 contour of mach no

The figures listed above are the contours obtained by the model 4. Figure-22 represents the contour of static pressure that signifies the formation of shock wave at the upstream of the cavity and the reflection of the shock wave at the downstream of the cavity which is due the presence of front ramp. Here, a maximum value of 868KPa pressure rise has been obtained near the wall in shock formation region. Figure-23 represents the contour of static temperature where a maximum value of 5322.44K is achieved inside the cavity that proves the capability of attaining flame stabilization process. Figure-24 represents the contour of turbulence kinetic energy which denotes a maximum turbulence value of 331076J/kg in the cavity where proper air-fuel mixture produced with vortex formation. Figure-25 represents the contour of total pressure that denotes a maximum value of 4.30e8KPa at the shock generating region. Figure-26 represents the contour of x-velocity where a minimum value of -1206.17m/s is achieved inside the cavity, negative sign indicates vortex region inside the cavity. Figure-27 represents the contour of mach number where a minimum value of 1.95 mach obtained in the cavity for a supersonic combustion process to occur.

VI. COMPARISON

The graphs for static pressure, static temperature, turbulence kinetic energy, total pressure, x-velocity and mach no are plotted for all the four models and compared below.

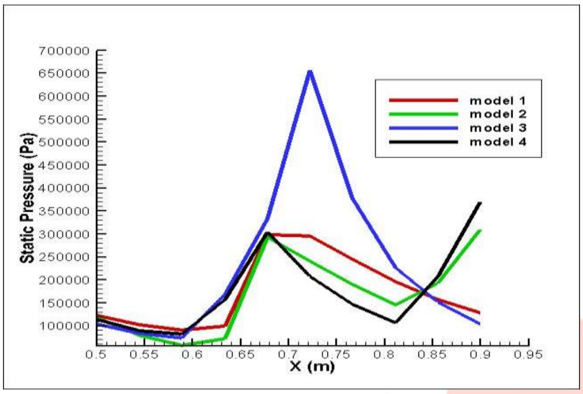

Fig-28 plot of static pressure

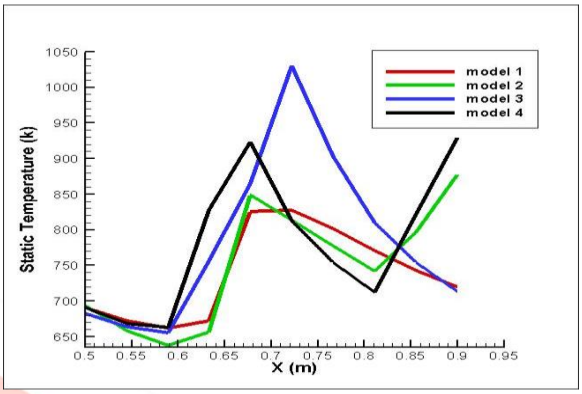

Fig-29 plot of static temperature

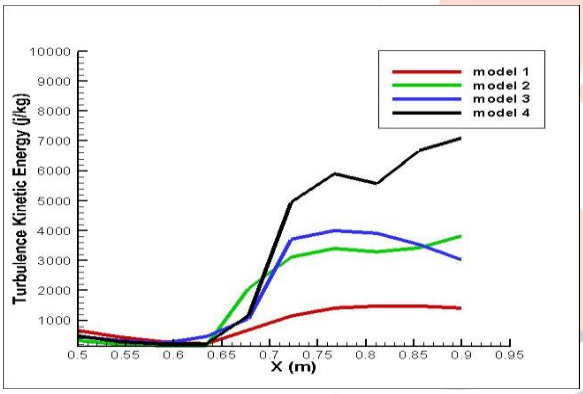

Fig-30 plot of turbulence kinetic energy

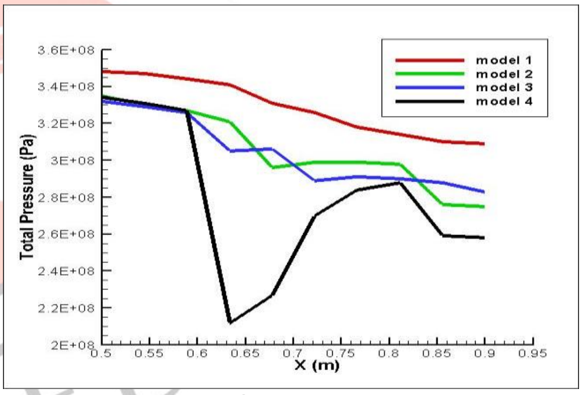

Fig-31 plot of total pressure

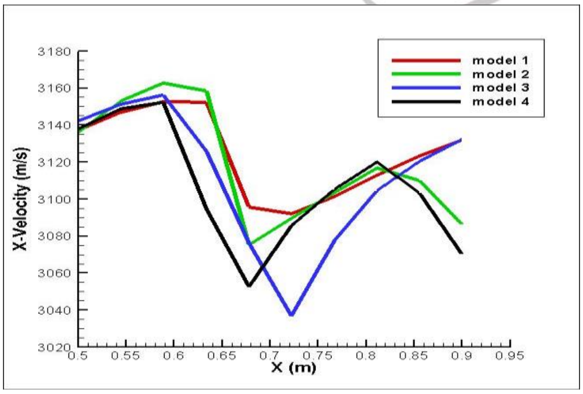

Fig-32 plot of x-velocity

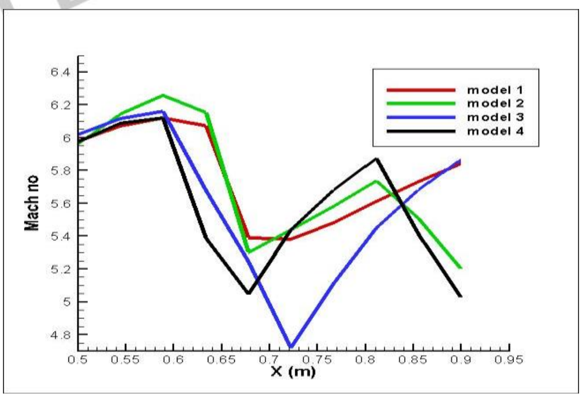

Fig-33 plot of mach no

In fig 28, the model with single cavity L/D ratio 5 with 15° front ramp angle (model 3) shows a better performance in static pressure when compared to other models. In figure-29, the model 3 shows a high rise in static temperature that possess a high flame holding capability. In figure-30, turbulence produced by model 4 is high when compared to other models where a high vortex formation can be seen in single cavity L/D ratio 10 with 15° front ramp angle. In figure-31, total pressure loss is high in the model 1 & 2 when correlated with model 3 & 4. In figure-32, a minimum velocity has been discovered with a very low supersonic recirculation region in model 3. In figure-33, mach number is maximum for 0° front ramp angle compared with 15° front ramp angles models.

VII. CONCLUSION

Eventually, in the present paper where the four models were analysed, model 3 i.e., single cavity with L/D ratio 5 with 15° front ramp angle shows high performance in terms of flame holding capabilities and single cavities with L/D ratio 5 and 10 with 15° front ramp angle shows better air-fuel mixture compared with single cavities with L/D ratio 5 and 10 with no front ramp angle. Similarly, the total pressure loss is maximum for single cavities L/D ratio 5 and 10 with no front ramp angle when compared to single cavities L/D ratio 5 and 10 with 15° front ramp angle. Hence, model 3 has a very better performance in terms of flame stabilization and turbulence region with low total pressure losses compared to other three models. Future work will be based on expanding the divergence section and back ramp angles with varying L/D ratios.

VIII. ACKNOWLEDGMENT

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