CFD Analysis on Performance of Open and Closed Single Cavity Based Scramjet Combustion at Mach 2

K.N.Jayachandran, N.Nithin, D.Thanikaivel Murugan

Abstract*— The proposal of supersonic combustion has become inevitable to fly at hypersonic speeds, but the problem of efficient mixing, flame holding and flame stabilization in supersonic combustors is yet to be overcome. Cavity based flame holders, which was used in subsonic combustors earlier is now extensively studied as supersonic combustor flame holders. The mixing characteristics of supersonic cavity flame holders depend on the formation of subsonic recirculation zone inside it. In this paper, open and closed single cavities with and without aft wall angle are analyzed to find out the optimum cavity configuration among them. The geometry was designed in ANSYS Design Modeler and the numerical analysis was done in ANSYS FLUENT 13.0 using the two dimensional density based energy equation and the turbulent characteristics are modeled using standard k-ε turbulence model. The contours of static pressure, static temperature, turbulence kinetic energy, total pressure and x-velocity were taken along the model length for comparison. From the results obtained, it is observed that cavity with L/D=10 and 45° aft wall angle showed better performance in terms of mixing characteristics and flame holding capability with no significant increase in total pressure loss compared to the other models. Single cavities with L/D=10 as well as cavities with aft wall angle showed better performance compared to single cavities with L/D=5 and with no aft wall angle respectively.

***Index Terms*— aft wall angle, supersonic combustion, single cavity, turbulence kinetic energy**

I. INTRODUCTION

Hypersonic air breathing engines namely scramjet engines have become the key focus in the development of future propulsion systems. But at this flight regime, the air entering the inlet of the scramjet engine will be at speeds above Mach 5 and the flow will be supersonic inside the combustor. Hence the process of fuel air mixing and flame holding for combustion within the short time is the major design problem. Different injection methods have been proposed for proper air fuel mixing and efficient flame holding which includes Parallel, Normal, Transverse injection, ramp, and strut, Cavity-Pylon Flame holder, Cavity Flame holders, Pylon Injection, upstream and pulsed injection.

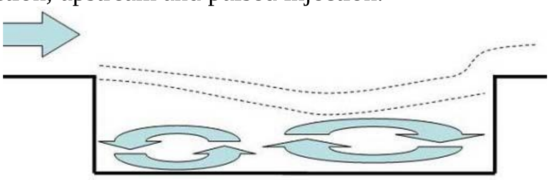

Fig -1: Flow through a cavity [3]

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Mr.K.N.Jayachandran, UG Final Year Student, Department of Aeronautical Engineering, Jeppiaar Engineering College, Chennai, India.

Mr.N.Nithin, UG Final Year Student, Department of Aeronautical Engineering, Jeppiaar Engineering College, Chennai, India.

Mr.D.Thanikaivel Murugan, Assistant Professor, Department of Aeronautical Engineering, Jeppiaar Engineering College, Chennai, India.

Among the various injection methods, a cavity flame holder as shown in Fig. 1 is an integrated fuel injection/flame holding approach used in scramjet combustors. The presence of a cavity in the vicinity of supersonic flow will have a significant impact on the flow parameters and forms a recirculation region which aids in flow mixing. Cavity in supersonic flow experiences fluctuations in density, velocity and pressure which induce self-sustained oscillations making the flow field analysis complex. Hence many experimental and theoretical studies have been done to understand the flow physics inside the cavity. In general, the cavities are classified into two types depending upon their length to depth ratio i.e., L/D ratio. Cavity with L/D <7-10 are known as open cavity and those with L/D>10-13 are known as closed cavity.

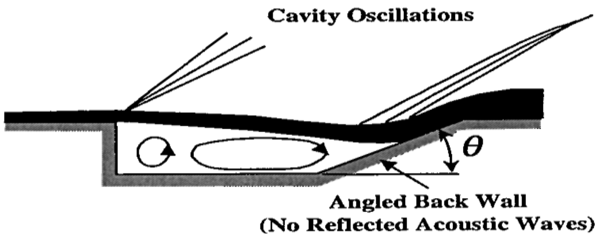

Fig -2: Cavity with aft wall angle [1]

Figure 2 shows a cavity with back ramp angle which is used to suppress the oscillations inside the cavity. Though cavity based flame holders provide excellent mixing characteristics, the potential problems of total pressure losses and drag penalties resists their extensive application in real flight conditions.

II. LITERATURE REVIEW

A detailed literature review of works on cavity based flame holders has been studied. Adela Ben-Yakar and Ronald K. Hanson[1] in their overview on cavity flame holders and flame stabilization for scramjet studied the flow field characteristics of cavities and summarized the research efforts related to cavities in low and high speed flows. J.Sandeep[2] & co studied the performance of cavities with L/D 3 & 5 and observed higher vorticity in L/D 3 cavity due to the presence of a single large vortex inside it. Also, they obtained maximum vorticity at a back angle of 22° in L/D 5 cavity. K. M. Pandey[3] & co studied an L/D 5 cavity with air intake and H2 injection at Mach number 2 and found out that a maximum temperature of 2100K is achieved with high thrust production and low shock formation using cavity flame holders. Oveespa Chakraborty[4] & co studied the mixing phenomena of single and double cavities for L/D ratio 10 and found that the mixing phenomena is more predominant in double cavity compared to the corresponding single cavity configuration. F.Xing & co[5] studied the performance of scramjet engine under non-reacting and reacting flow conditions with a corner plate at the leading edge of the cavity. They found that the distance of corner plate from the front wall affects the mixing characteristics in a cavity and controls the fuel rich regions within it.

From the previous literature on cavity flame holders, it is very clear that closed cavities are not extensively researched as the case of open cavities. Though the effect of aft wall angle on suppressing the cavity oscillations are very well understood, their effect on flow field parameters have to be studied in detail. So, the present paper discusses both open and closed single cavities with and without aft wall angle to find out the optimum cavity configuration.

III. METHODOLOGY

After studying the previous literature on cavities as supersonic combustor flame holders, the geometry of the models were designed in ANSYS Design Modeler and the meshing operation was performed in ANSYS Mesh. Further, the meshed models were numerically analyzed in ANSYS FLUENT 13.0 and the contours of static pressure, static temperature, turbulence kinetic energy, total pressure and x-velocities along the combustor length are taken for comparison.

IV. NUMERICAL ANALYSIS

A. Geometry

As stated earlier, the models were designed in ANSYS Design Modeler with the dimensions of the four models as shown in Table 1.

B. Meshing

The designed models were meshed in ANSYS Mesh by means of triangular mesh which provides greater accuracy.

C. Boundary Conditions

Finally, pressure far field and pressure outlet conditions are given at the inlet and outlet boundaries with a Mach 2 flow at the inlet. The wall is taken as stationary wall with no slip conditions at the boundary. The initial conditions are as shown in Table 2.

Table -1: Model Dimensions

Model	**1**	**2**	**3**	**4**
L/D ratio	5	10	5	10
Length of cavity	100 (mm)	200 (mm)	100 (mm)	200 (mm)
Inlet	54.5 (mm)	54.5 (mm)	54.5 (mm)	54.5 (mm)
Length of combustor	835 (mm)	835 (mm)	835 (mm)	835 (mm)
Length of divergence section	1144 (mm)	1144 (mm)	1144 (mm)	1144 (mm)
Divergence angle	2°	2°	2°	2°
Aft wall angle	0°	0°	45°	45°

Table -2: Initial Conditions

Parameters	Conditions
Air	Ideal gas
Mach no	2
Gauge pressure	101325 Pa
Temperature	1000 K

V. RESULTS AND DISCUSSION

For the purpose of analysis, implicit two dimensional energy equations and k-ε turbulence model has been used. The iterations are run until the residuals converged and the solution attained a steady state. The contour of static pressure shows the formation of shocks and expansion waves near and around the cavity. The contours of static temperature indicate the regions of high temperature where the flame holding capability of the cavity is higher. The contours of turbulence kinetic energy clearly indicate the mixing performance of cavity. The contours of total pressure indicate the pressure losses inside the cavity. The contours of x-velocity indicate the presence of subsonic recirculation region inside the cavity.

A. Single cavity of L/D=5 without aft wall angle

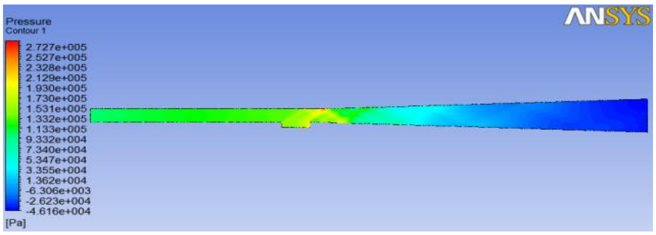

Fig -3: Contour of Static Pressure

Figure 3 shows the contour of static pressure for model 1, which shows weak shock formation at the upstream of the cavity and strong shocks form at the downstream of the cavity. Due to the formation of shocks, there is a rise in static pressure to a maximum value of about 282 kPa at the top wall above the trailing edge of the cavity.

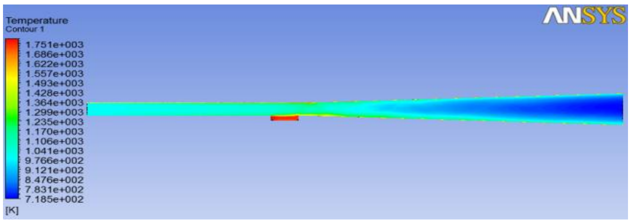

Fig -4: Contour of Static Temperature

From Fig. 4, it is seen that the temperature increases inside the cavity and reaches a maximum value of about 1783.22 K, which indicates the flame holding efficiency of the cavity.

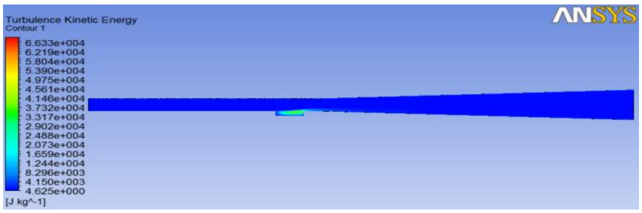

Fig -5: Contour of Turbulence Kinetic Energy

It is observed from Fig. 5 that the turbulence kinetic energy reaches a maximum of about 68,407.2 J/kg which shows the mixing capability of the cavity due to the formation of vortex inside the cavity.

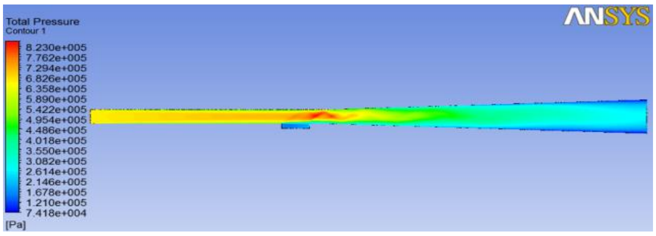

Fig -6: Contour of Total Pressure

Figure 6 shows the contour of total pressure, which clearly indicates total pressure loss inside the cavity to a minimum of about 74 kPa and sharp increases of total pressure at the shock formation regions to about 846 kPa.

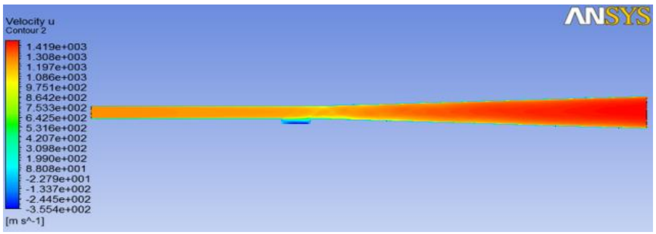

Fig -7: Contour of X-Velocity

The contour of x-velocity is shown in Fig. 7 and it clearly indicates that the flow reaches subsonic values inside the cavity due to the formation of a recirculation region. The x-velocity reaches a minimum of -355.421 m/s inside the cavity.

B. Single cavity of L/D=10 without aft wall angle

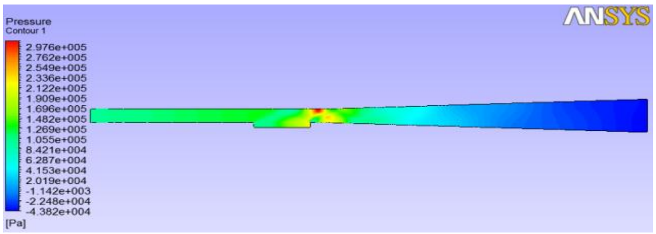

Fig -8: Contour of Static Pressure

Figure 8 shows the contour of static pressure for model 2, from which the formation of shock waves and expansion waves is visualized and a maximum pressure of about 308 kPa occurs at the regions of shock.

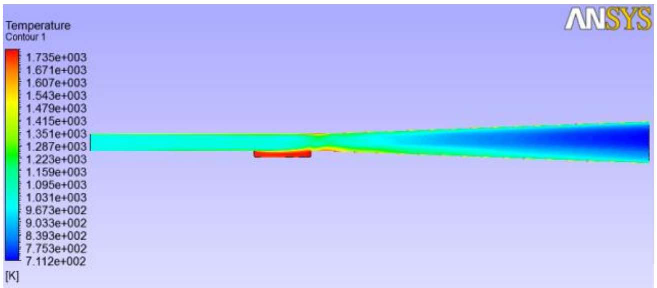

Fig -9: Contour of Static Temperature

In Fig. 9, it is seen that the static temperature increases to a maximum of 1767.4 K at the inside of the cavity which is slightly less than that of model 1.

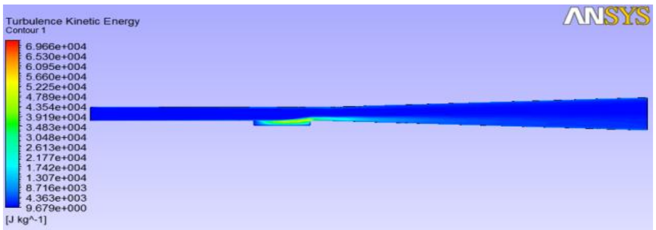

Fig -10: Contour of Turbulence Kinetic Energy

From Fig. 10, it is shown that the turbulence kinetic energy reaches a maximum of 71,833.7 J/kg inside the cavity.

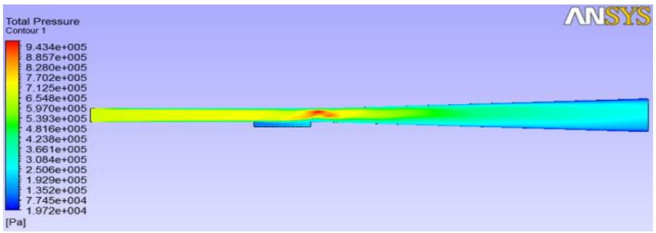

Fig -11: Contour of Total Pressure

The contours of total pressure in Fig. 11 shows low values inside the cavity of about 19 kPa and increases to a maximum of 972 kPa at the shocks.

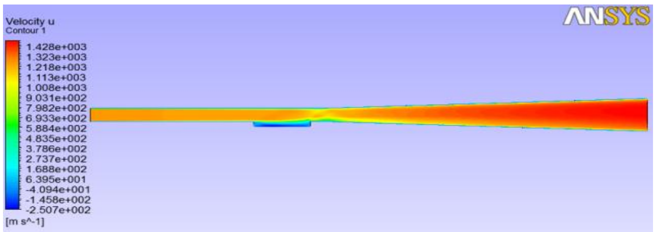

Fig -12: Contour of X-Velocity

From Fig. 12, it is observed that the x-velocity reaches a minimum of about -250.73 m/s inside the cavity due to the recirculation of flow.

C. Single cavity of L/D=5 with 45° aft wall angle

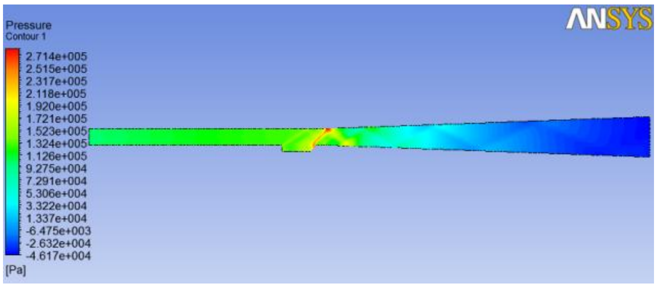

Fig -13: Contour of Static Pressure

Figure 13 show the contour of static pressure for model 3, which indicates a maximum pressure of 281 kPa at the trailing edge shock. The static pressure contour of model 3 is similar to model 1 and the shock formations are also similar.

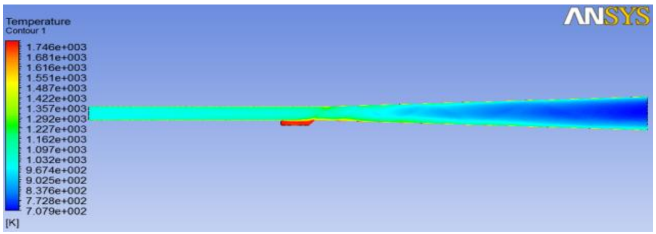

Fig -14: Contour of Static Temperature

From Fig. 14, it is seen that the temperature increases to a maximum value of about 1778.53 K inside the cavity.

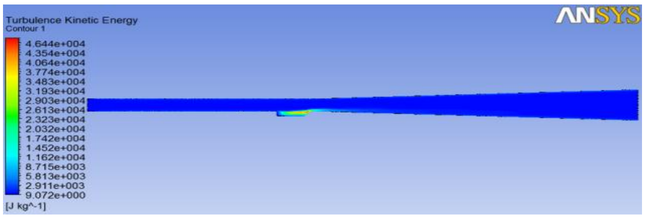

Fig -15: Contour of Turbulence Kinetic Energy

Figure 15 shows the contour of turbulence kinetic energy for model 3, which indicates mixing capability of the cavity with shows a maximum value of 47,892 J/kg.

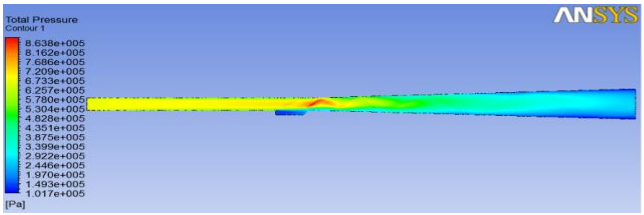

Fig -16: Contour of Total Pressure

The contour of total pressure for model 3 is also similar to model 1 except for a maximum and minimum value of about 887 kPa and 101 kPa as shown in Fig. 16.

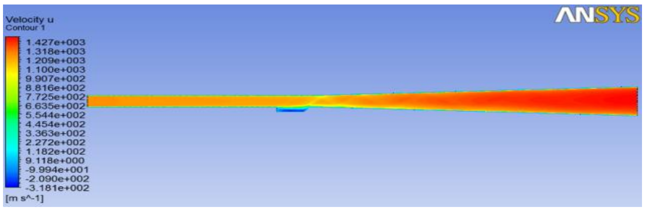

Fig -17: Contour of X-Velocity

The x-velocity reaches a minimum of about -318.06 m/s inside the cavity as seen in Fig. 17.

D. Single cavity of L/D=10 with 45° aft wall angle

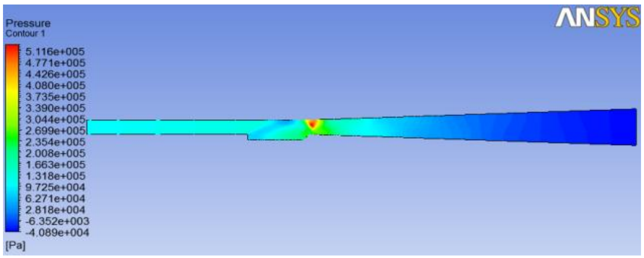

Fig -18: Contour of Static Pressure

As seen in Fig. 18, the formation of shocks and expansion waves for model 4 is similar to model 2 but with a maximum value of about 528 kPa at the regions of shocks at the trailing edge of the cavity.

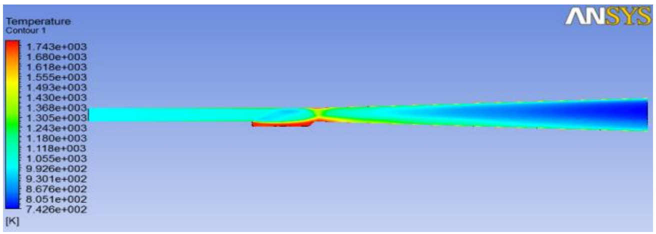

Fig -19: Contour of Static Temperature

The contour of static temperature shows a maximum temperature of 1773.75 K inside the cavity as shown in Fig. 19.

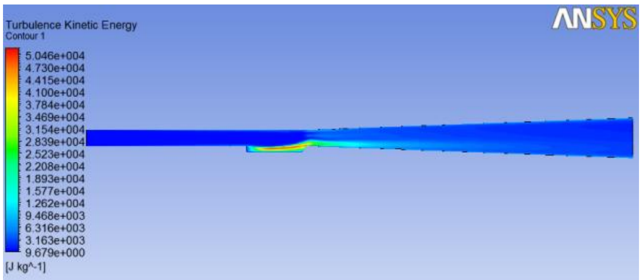

Fig -20: Contour of Turbulence Kinetic Energy

In Fig. 20, the contour of turbulence kinetic energy indicates a turbulent flow inside the cavity with a maximum value of 52,032.7 J/kg.

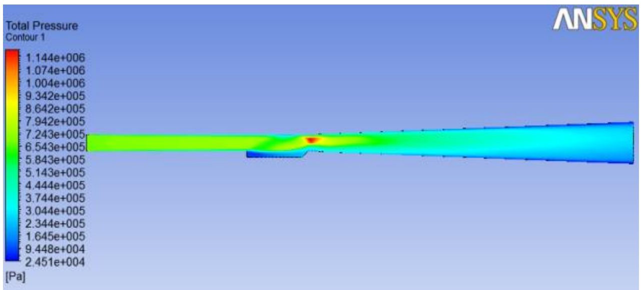

Fig -21: Contour of Total Pressure

The contours of total pressure for model 4 is similar to model 2 with total pressure loss inside the cavity with a minimum value of about 24 kPa and maximum value of about 1,179 kPa at the shocks is observed from Fig. 21.

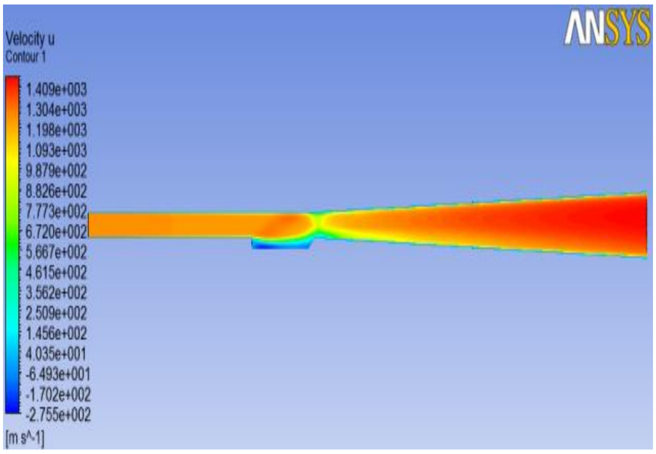

Fig -22: Contour of X-Velocity

From Fig. 22, it is easily inferred that the x-velocities reaches a minimum value of about -275.49 m/s inside the cavity.

VI. COMPARISON

The plots of static pressure, static temperature, turbulence kinetic energy, total pressure and x-velocity along the centre line of the combustor are taken for comparison.

It is clear from Fig. 23 that for cavities with L/D=10, there is a drop in pressure at the leading edge of the cavity which indicates the formation of expansion waves at the leading edge. Due to oscillations present in cavities with L/D=5, there is no expansion waves formed, instead a weak shock is formed at the leading edge. The presence of aft wall angle increases the strength of shocks formed.

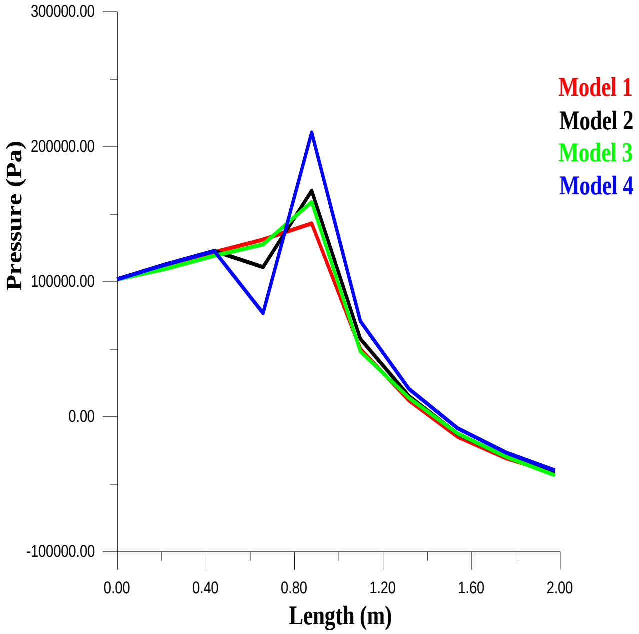

Fig -23: Comparison of Static Pressure

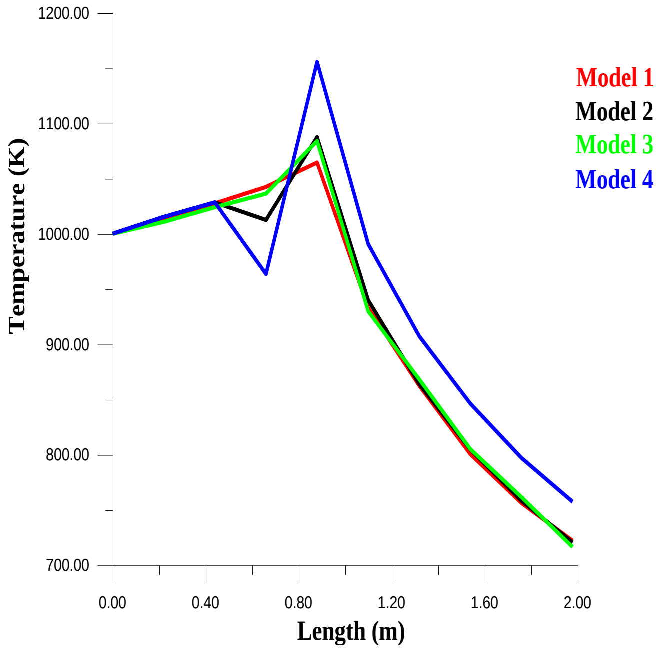

Fig -24: Comparison of Static Temperature

From Fig. 24, Model 4 has the highest rise in static temperature which enhances its flame holding capability though the temperature is low at leading edge of the cavity. Also, the presence of aft wall angle increases the flame holding capability of the cavity.

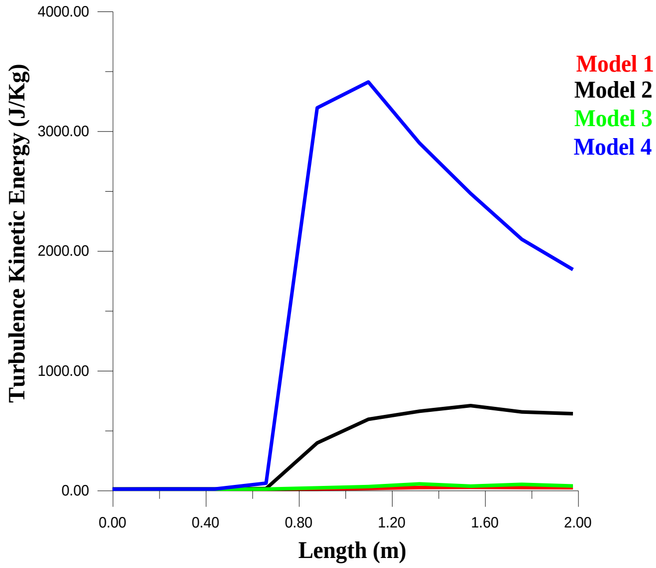

Fig -25: Comparison of Turbulence Kinetic Energy

From Fig. 25, it is viewed that model 4 has the highest mixing performance though the problem of turbulence being still large at the outlet is a concern. In general, the presence of aft wall angle enhances the mixing performance.

The comparison of total pressure from Fig. 26 clearly indicates that there is only slight variation in total pressure loss due to the change in L/D ratio and aft wall angle.

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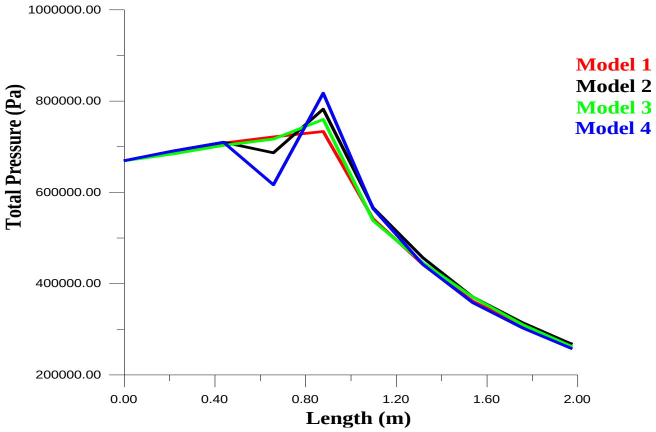

Fig -26: Comparison of Total Pressure

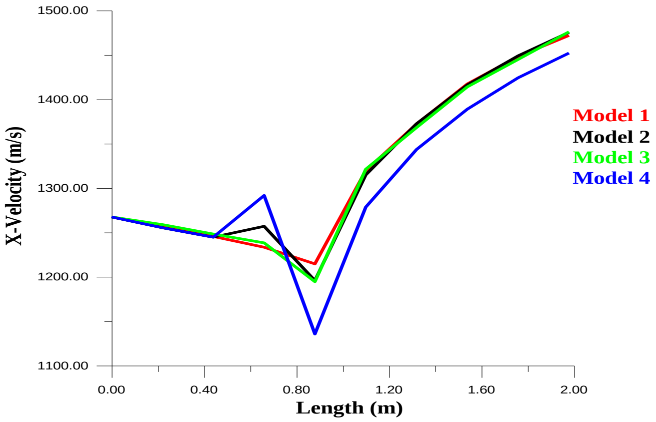

Fig -27: Comparison of X-Velocity

Model 4 has the highest decrease in x-velocity which clearly means that very low speed regions are created inside the cavity which enhances mixing and recirculation as shown in Fig. 27.

VII. CONCLUSION

The four single cavity models are analyzed and compared in the present paper. Model 4 i.e., Single cavity of L/D=10 with aft wall angle 45° is considered to be superior in terms of mixing and flame holding efficiencies with no significant increase in total pressure loss. In general, single cavities with L/D=10 and aft wall angle 45° showed better performance compared to cavities with L/D=5 and zero aft wall angle respectively. In future, multi cavities with varying L/D ratio and ramp angles will be studied.

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