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CFD Analysis of Single and Double Cavity Based Scramjet Combustion with Front Ramp Angle at Mach 2

K. N. Jayachandran[1], N. Nithin[2], D. Thanikaivel Murugan[3]

[12]UG Final Year Student, Department of Aeronautical Engineering, Jeppiaar Engineering College, Chennai, India
[3]Ph.D. Research Scholar[3], Department of Aeronautical Engineering, Sathyabama University, Chennai, India

Abstract: Modern high speed aerospace propulsion relies on the development of scramjet engines significantly. Design of a supersonic combustor involves the potential problems of proper mixing, flame holding as well as flame stabilization within the very short period. Many techniques were introduced to overcome these problems, of which cavity flame holders has evolved as one of the prominent among them. The presence of cavity forms a recirculation region inside the combustor, which enhances fuel-air mixing and flame holding. The aim of this paper is to analyze and compare cavities of L/D ratio 5 & 10 in single and double cavity configurations with a front ramp angle. The models were designed in ANSYS Design Modeler and the numerical simulation was done in ANSYS FLUENT 13.0 using the two dimensional density based energy equation and k- ε turbulence model. The contours of static pressure, static temperature, turbulence kinetic energy, total pressure and x-velocity are taken along the combustor length for comparison. Double and closed cavities were more efficient in terms of mixing and flame holding characteristics compared to the corresponding single and open cavities respectively though the total pressure losses are higher for the former models.

Index Terms: cavity, supersonic combustor, front ramp angle, recirculation, mixing, numerical simulation

Introduction

Two decades back, ramjet engines have been the focus of high speed air-breathing propulsion especially in the supersonic flight regimes. The need and desire to fly at even higher speeds led to the development of supersonic combustion ramjets, famously known as scramjet engines. Scramjet engines have to fly at hypersonic speeds during which the flow inside the combustor will be supersonic in contrast to subsonic combustors previously used. In the case of supersonic combustors, proper fuel-air mixing, efficient combustion and flame holding within milliseconds are the major obstacles to be overcome. Various methods have been proposed to overcome these difficulties of which cavity based flame holders are one of the prominent.

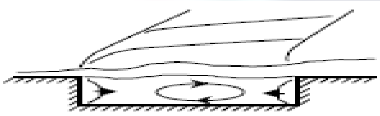

Fig. 1. Open cavities of L/D ratio < 7-10[7]

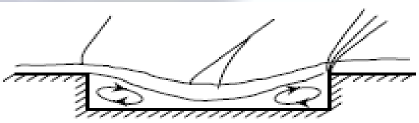

Fig. 2. Closed cavities of L/D ratio > 10-13[7]

Cavity flame holders were first developed by the Central Institution of Aviation Motors (CIAM), Moscow in a dual mode scramjet flight test. In the case of cavity based scramjet combustion, a subsonic recirculation region is created inside the cavity which promotes fuel-air mixing and flame holding purposes. In general, cavities are classified depending upon their length to depth ratio (L/D) as open and closed cavities as shown in the Fig. 1 & 2 respectively. In the case of open cavities, the detached shear layer at the leading edge of the cavity reattaches at the trailing edge and induces self-sustained oscillations inside the cavity. But in closed cavities, the shear layer usually reattaches at the base wall of the cavity.The formation of vortex inside the cavity is also clearly visible. For the purpose of suppressing the oscillations, usually an angled wall at trailing edge is used. In the recent past, for enhancing the mixing characteristics, multi-cavity flame holders were developed. The presence of double cavity increases the total pressure losses and hence many researchers have tried to minimize these losses by introducing various ramp angles and by changing the size, shape and location of the cavities.

Literature review

A detailed literature survey on cavity as flame holders in supersonic flow has been studied and some of the important works are as follows. K. M. Pandey and T. Sivasakthivel[1] in their review on recent advances in scramjet fuel injection discussed the various techniques for fuel injection in supersonic flow including cavity based fuel injection and also discussed their advantages and disadvantages. Adela Ben-Yakar and Ronald K. Hanson[2] 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 flow. They also observed that cavities with aft ramp angle between 45° and 16° yields minimum drag penalties. J.P. Kalita[3]& co studied the supersonic combustion of hydrogen fuel using cavity-based fuel injector of L/D ratio 5 with two-dimensional turbulent non-premixed combustion model and found a maximum temperature of 1789K at the exit of the combustor. 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. DingwuZhanga and Qiang Wanga[5] studied cavities with front ramp angles of 15°,30°,-15°,-30° and found out that the mixing effects show significant improvement when the ramp angle is positive, however, over-large ramp angle could add resistance and reduce total pressure recovery. They found out that cavity with 15° front ramp angle showed the best performance. K.N. Jayachandran, N. Nithin and D. Thanikaivel Murugan[6] studied the performance of open and closed single cavities and found out that closed cavities and cavities with aft wall angle showed superior performance compared to open cavities and cavities without aft wall angle respectively.

Looking through the various research works conducted previously, very few works were on double cavity configurations and the effect of front ramp angle on mixing characteristics is not yet fully understood. So, the main goal of this paper is to analyze and compare the performance of single and double cavities having both a front ramp angle of 15° and a back ramp angle of 45°.

Methodology

Initially, the flow-field and mixing characteristics of cavity flame holders in supersonic combustor was studied in detail. The geometry of the models was designed in ANSYS Design Modeler. Then, the designed models were meshed in ANSYS Mesh by means of triangular nodes. Finally, the meshed models were analyzed in ANSYS FLUENT 13.0 using the two dimensional density based energy equation and k-ε turbulence model. The contours of various flow parameters are taken to understand the flow-field inside the cavity. A comparison has been made amongst the static pressure, static temperature, turbulence kinetic energy, total pressure and x-velocity along the centerline of the combustor length for the four models mentioned in Table 1.

Numerical Analysis

A. Geometry

Table 1 Model Dimensions

Model	1	2	3	4
Type	Single	Single	Double	Double
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	45°	45°	45°	45°
Front ramp angle	15°	15°	15°	15°

First, the two dimensional geometry of the four models were designed in ANSYS Design Modeler withthe dimensions of the models as shown in Table 1.

B. Meshing

Following the design of geometry, all the models were meshed in ANSYS Mesh by means of triangular nodes. The models were fine meshed using All Triangles Method. The selection of triangular mesh is due to its high accuracy compared to the other types of mesh although the convergence of the solution may take more time.

C. Boundary conditions

For any kind of analysis, proper initial conditions and boundary conditions are to be provided. Pressure far field and pressure outlet conditions were taken at inlet and outlet boundaries respectively with a Mach 2 flow at the inlet. The wall conditions are taken as stationary wall with no slip at the wall boundary.

Results and Discussion

Finally, the analysis was done in ANSYS FLUENT 13.0 by means of implicit method and first order upwind discretisation were taken for solution. The iterations were made to run until all the residuals attain a steady state. The contours of static pressure, static temperature, turbulence kinetic energy, total pressure and x-velocity for the various models are as follows.

A. Single cavity of L/D=5 with 15° front ramp angle

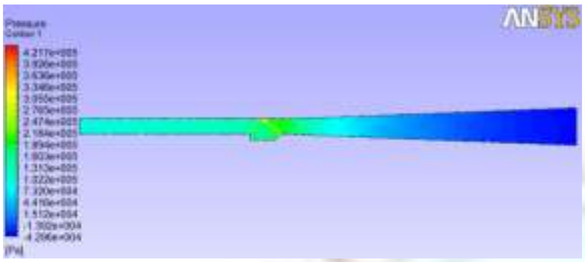

Fig. 3.Contour of Static Pressure

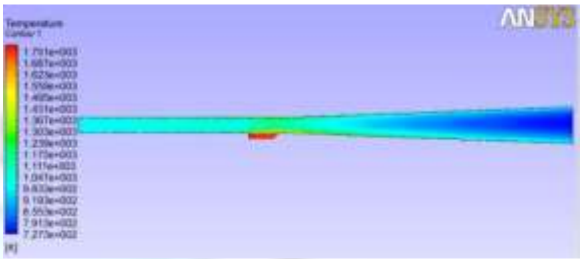

Fig. 4. Contour of Static Temperature

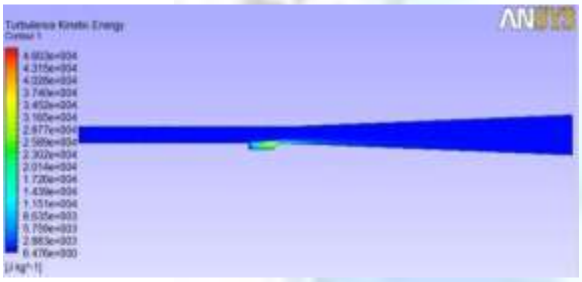

Fig. 5.Contour of Turbulence Kinetic Energy

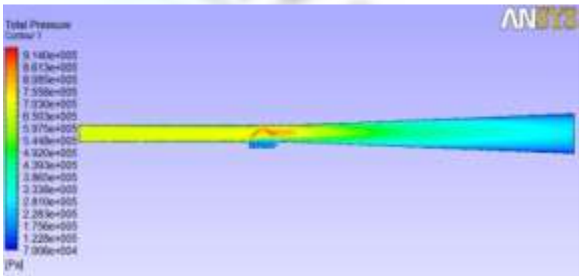

Fig. 6. Contour of Total Pressure

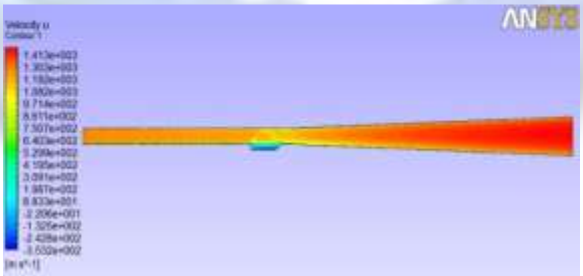

Fig. 7. Contour of X-Velocity

The contour of static pressure for model 1 is shown in Fig. 3. It is observed that the shocks were formed in and around the cavity and the pressure reaches a maximum value of about 436 kPa at the top wall. Due to the presence of front ramp angle, there is a strong shock formed at the leading edge of the cavity which may enhance the combustion process.The contours of static temperature as in Fig. 4 clearly shows very high temperatures formed inside the cavity having a maximum value of about 1783.42 K. The rise in temperature is a direct measure of the flame holding capability of the cavity.From Fig. 5, it is seen that the turbulence kinetic energy increase to about 47,466.1 J/kg inside the cavity which indicates the formation of vortex inside the cavity enhancing the mixing characteristics.In Fig. 6, it can be viewed that the total pressure decreases to very low values inside the cavity of about 70 kPa while increasing to peak values of about 940 kPa at the shock forming regions.

This clearly indicates loss of total pressure due to the presence of cavity.The contour of x-velocity for model 1 as shown in Fig. 7 clearly indicates a subsonic flow inside the cavity mainly due to the formation of a recirculation region. The x-velocity deceases to about -353.23 m/s inside the cavity. The negative values of x-velocity indicate reverse flow in the cavity due to vortex formation.

B. Single cavity of L/D 10 with 15° front ramp angle

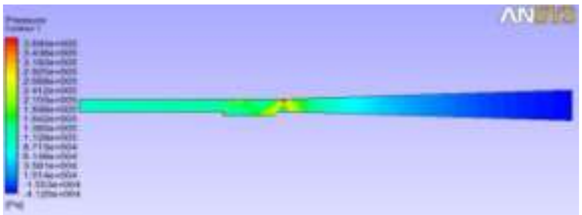

Fig. 8.Contour of Static Pressure

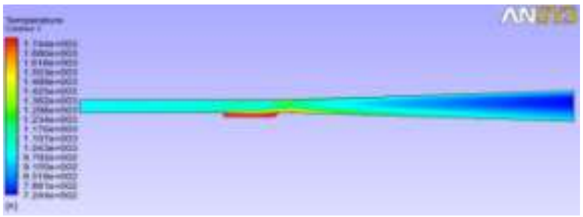

Fig. 9. Contour of Static Temperature

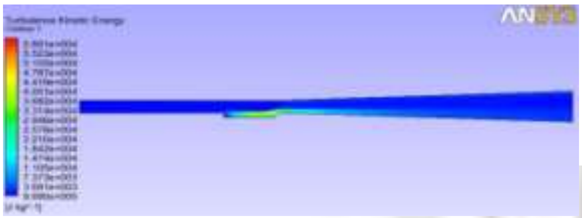

Fig. 11.Contour of Total Pressure

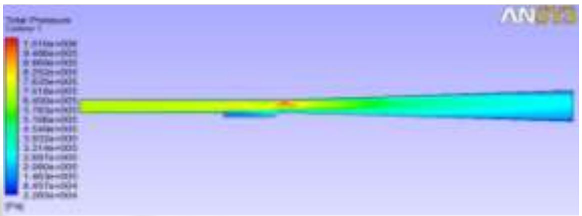

Fig. 10. Contour of Turbulence Kinetic Energy

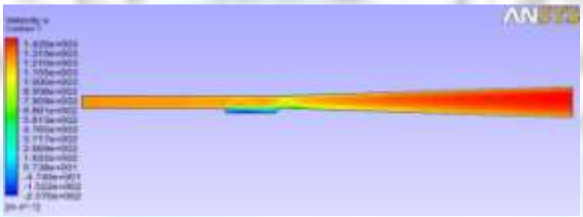

Fig. 12. Contour of X-Velocity

Figure 8 shows the contour of static pressure for model 2 which clearly shows the location and strength of the shocks. The strong shock formed at the top wall has maximum strength of about 382 kPa.As seen in Fig. 9, the static temperature increases to very high values inside the cavity of the order of about 1775.68 K.From Fig. 10, it can be inferred that the turbulence kinetic energy reaches a maximum value of about 60,754.9 J/kg inside the cavity.As in Fig. 11, the total pressure values increases to a maximum of about 1041 kPa at the shocks and decreases to very low values of about 22 kPa inside the cavity.The contour of x-velocity as in Fig. 12 clearly indicates a very low value of about -256.96 m/s inside the cavity.

C. Double cavity of L/D 5 with 15° front ramp angle

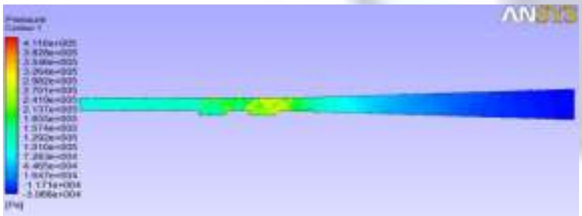

Fig. 13.Contour of Static Pressure

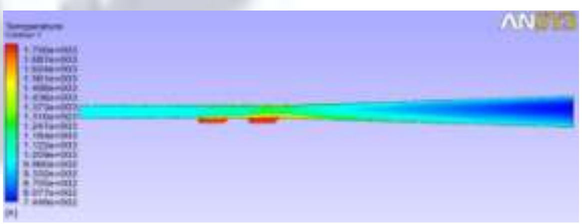

Fig. 14. Contour of Static Temperature

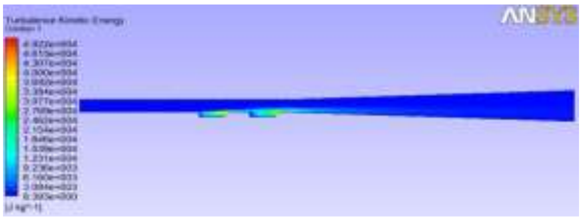

Fig. 16.Contour of Total Pressure

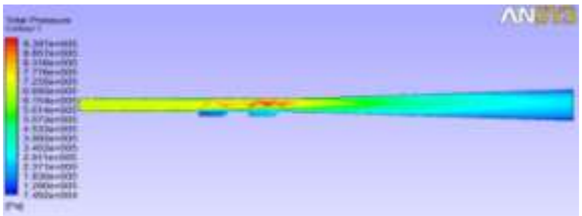

Fig. 15. Contour of Turbulence Kinetic Energy

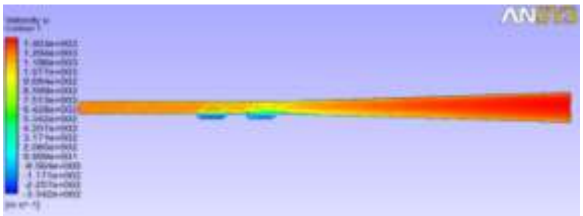

Fig. 17. Contour of X-Velocity

For model 3, the static pressure contour clearly shows that the strength of the shocks are higher near the second cavity with a maximum value of about 425 kPa as in Fig. 13. From Fig. 14, it is seen that the temperature reaches a maximum value of about 1780.9 K inside the cavities.As shown in Fig. 15, the turbulence kinetic energy attains a maximum of about 50,762.3 J/kg at the back wall of the cavity.The total pressure values increases to maximum of about 966 kPa across the shocks and decreases to minimum of about 74 kPa inside the cavity as seen in Fig. 16.From Fig. 17, it can be viewed that the x-velocity decreases to minimum of about -334.22 m/s inside the cavity.

D. Double cavity of L/D 10 with 15° front ramp angle

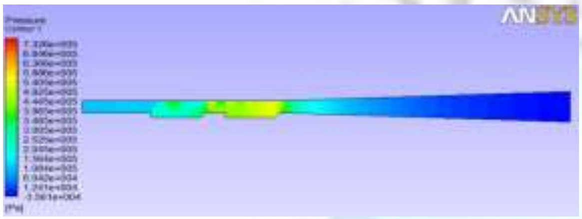

Fig. 18.Contour of Static Pressure

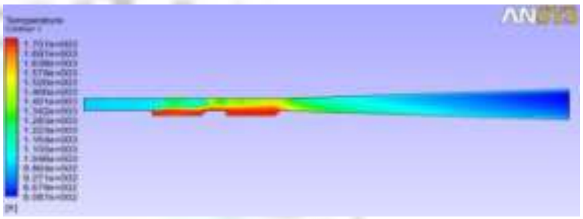

Fig. 19. Contour of Static Temperature

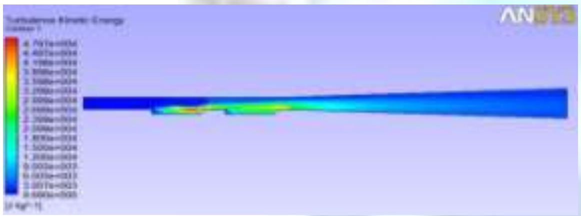

Fig. 20.Contour of Turbulence Kinetic Energy

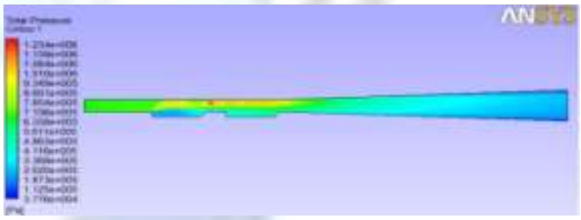

Fig. 21. Contour of Total Pressure

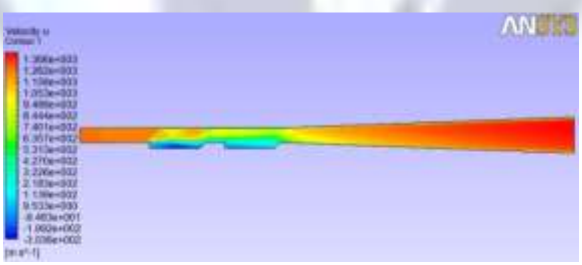

Fig. 22. Contour of X-Velocity

From Fig. 18, the formation of shocks at the vicinity of the cavities for model 4 can be seen with a maximum pressure value of about 756 kPa.In Fig. 19, the contour of static temperature clearly indicates a maximum value of about 1786.19 K inside the cavity.As seen in Fig. 20, the turbulence kinetic energy reaches a maximum of about 49,469.5 J/kg inside the cavities.From Fig. 21, it can be seen that the total pressure increases to a maximum of about 1,271 kPa across the shocks while attaining low values of about 37 kPa inside the cavity. The contour of x-velocity reaches low subsonic values inside the cavities with a minimum value of about -303.55 m/s as seen in Fig. 22.

Comparison

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

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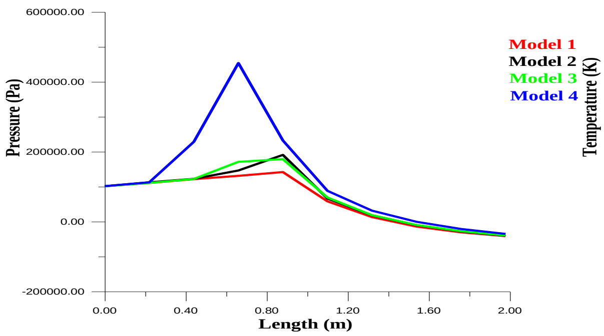

Fig. 23.Comparison of Static Pressure

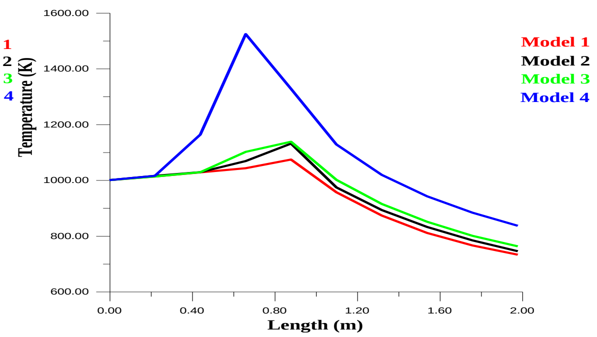

Fig. 24. Comparison of Static Temperature

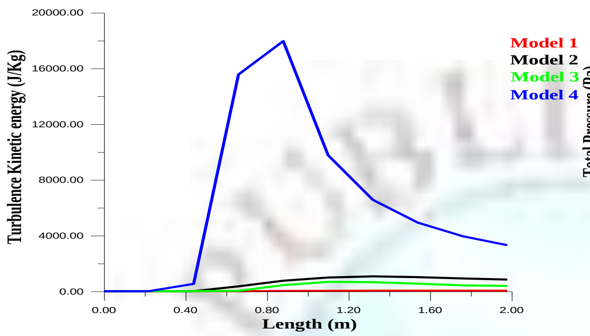

Fig. 25.Comparison of Turbulence Kinetic Energy

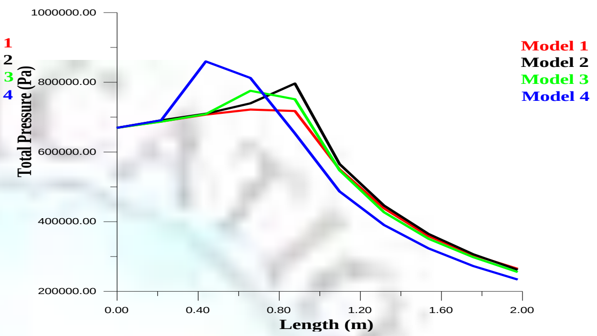

Fig. 26. Comparison of Total Pressure

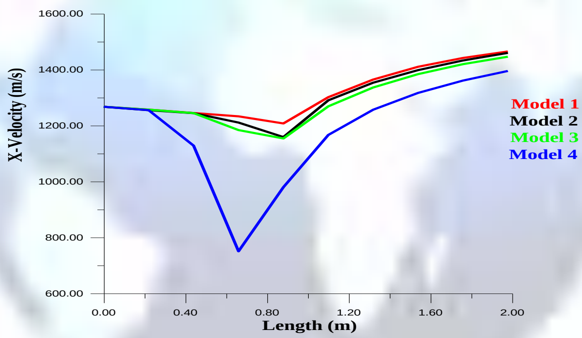

Fig. 27. Comparison of X-Velocity

From Fig. 23, it clear that model 4 has the highest rise in static pressure. Double cavities show higher pressure rise compared to single cavities. At the same time, cavities with L/D=10 show higher rise in pressure compared to cavities with L/D=5.In Fig. 24, it is seen that model 4 has the highest rise in static temperature inside the cavity. It indicates that it is the best model in terms of flame holding which in turn promotes ignition and combustion downstream when fuel is used.From Fig. 25, it can be observed that model 4 is the best in terms of mixing performance due to the high value of turbulence kinetic energy. Yet the problem of turbulence being still higher at the outlet is a major concern. Comparing the total pressure values of the models as in Fig. 26, it can be concluded that the total pressure loss due to the presence of cavity is comparatively higher for model 4.In Fig. 27, it can be shown that the x-velocities reduce to subsonic values in model 4 compared to the other models which indicates the presence of a very low subsonic recirculation region for mixing.

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Conclusion

In the present study, the four cavity based models were analysed and compared. From the results obtained, model 4 i.e., double cavity of L/D=10 with 15° front ramp angle is considered to be superior in terms of mixing as well as flame holding capabilities compared to the other models though the total pressure losses are slightly higher for this model. In general, double cavities exhibit better mixing and flame holding capabilities compared to single cavities. Also cavities with L/D=10 show better performance compared to cavities with L/D=5. The future work will focus on studying cavities with varying front ramp angles and different L/D ratio.

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