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Technical Notes

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Experimental Investigations on Supersonic Stream Past Axisymmetric Cavities

S. Jeyakumar
Dr. Sivanthi Aditanar College of Engineering, Tiruchendur, Tamil Nadu 628 215, India
P. Balachandran
Indian Space Research Organization, Thiruvananthapuram 695 547, India
and
S. Indira
National College, Trichy, Tamil Nadu 620 002, India

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Nomenclature

a = cavity aspect ratio L/D of 1.25
b = cavity aspect ratio L/D of 0.71
L/D = length to depth ratio of the cavity
L_m/D_m = length to diameter ratio of the mixing tube
T_o = stagnation temperature
σ = standard deviation
ϕ = uniformity factor

Subscripts

av = average value
i = properties of primary jet at nozzle exit
un = unmixed condition

I. Introduction

IN supersonic combustion ramjet engines the fundamental aspects are fuel injection, ignition, and flame holding. An efficient fuel-injection system is needed for mixing of air and fuel within a short combustor to achieve successful combustion. Different injection systems have been proposed [1–4] for rapid mixing of air and fuel, including both flush-mounted and intrusive injectors. However, these injection systems do not initiate the combustion process. The other two important factors that affect the design of fuel-injection systems are ignition and flame holding [5]. Once ignition is established, the efficiency of combustion depends on mixing of air and fuel. The goal of the flame holder is to reduce the ignition delay and to provide a continuous source for the chemical reaction to be established within a short distance. Flame holding can be achieved by generating a recirculation area and the interaction of shock waves in the flowpath. However, these stabilization techniques [6] have the drawback of increased total pressure loss due to strong bow shock waves in the flowpath.

Recent publications have presented the advantage of cavities for both fuel injection and flame holding in supersonic combustion engines [7,8]. A cavity exposed to a flow can be classified in two categories based on the shear layer that separates from the upstream lip and reattaches downstream. For $L/D < 10$, the cavity is termed open, because 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. For $L/D > 10$, the cavity flow is termed closed, because the free shear layer reattaches at the bottom of the cavity wall. The pressure increases in the back-wall vicinity and decreases near the front wall, resulting in large drag losses. Open cavities are further classified into deep and shallow cavities. Deep cavities act as resonators and the shear layer above the cavity acts as a forcing mechanism. In shallow cavities, the standing longitudinal acoustic waves propagate disturbances, which get amplified through the shear layer. On this basis, the cavities may be considered shallow for $L/D > 1$ and deep for $L/D < 1$.

Yu and Schadow [9] used rectangular wall-mounted cavities to enhance mixing in supersonic jets. The cavities were straight and semi-annular types and were rectangular in cross section. Their results revealed that the cavity-actuated forcing reduced the afterburning flame length by 30% with modified intensity. Vinogradov et al. [10] experimentally investigated scramjet combustors operating on kerosene, where cavities were used as flame holders. A row of hydrogen fuel injectors placed in front of a cavity was used to achieve sustained combustion. Ben–Yaker and Hanson [8] experimented with high total-temperature high-speed flows over cavities to understand the fluid dynamics and flame holding characteristics. Their results reveal the details of an oscillating shear layer at the lip of the cavity moving into an oscillatory boundary layer downstream of the cavity and an array of the shock pattern.

Yu et al. [12] conducted experiments on combustion stabilization in a liquid-kerosene-fueled model Scramjet combustor, using the concepts of effervescent atomization with either air or hydrogen being a barbotage gas, with a cavity flame holder. The entry Mach number was fixed at 2.5 and the total pressure and temperature of vitiated air varied around 1.0–1.3 MPa and 1700–1900 K, respectively. Barbotaged atomization using hydrogen promoted the overall burning and increased the combustion efficiency by 15–20% compared with the pure liquid atomization case. The combustion performance was found to increase with increasing cavity depth, which essentially characterized the cavity residence time. Further increasing the depth of the cavity flame holder from 12 mm was found to provide less variation in combustion performance.

Yu et al. [13] have investigated the stable and unstable characteristics of a cavity flow with an emphasis on the phenomena of flow-induced cavity resonance. It was found that the stable and unstable cavities could be used for flame holding and mixing enhancement, respectively. As such, combining open and closed cavities in tandem would be a promising approach to provide both flame holding and mixing enhancement. The present study examines quantitative mixing and total pressure drop of supersonic streams past wall-mounted axisymmetric cavities.

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II. Details of Experiment

Figure 1 shows the schematic diagram of the test setup employing two coaxial jets. The conventional convergent–divergent nozzle provides the primary jet, whereas the secondary jet passes through the annular convergent passage around the primary nozzle. The primary nozzle provides a flow Mach number of 1.32 and the secondary flow is choked. The stagnation temperature of the primary air is maintained at 1050 K by regulating the fuel flow to the primary subsonic combustor; the secondary air temperature is at room temperature (305 K). The primary and secondary flows enter a mixing tube of circular cross section, which is attached at the exit of the nozzles. The aspect ratios L_m/D_m of the mixing tubes used for the study are 3.6, 4.2, and 5.0. Figure 2 shows the end view of the mixing tube assembly. The cavities are attached at the flow inlet of the mixing tube. Single, twin, and triple cavity configurations are arranged in tandem. They are denoted by cavity configurations 1, 2, and 3. The cavities used for the analysis are open type and axisymmetric with constant length (10 mm), whereas the depth of the cavity varies (8 and 14 mm), i.e., length to depth ratio of the cavities are 1.25 and 0.71.

The measurements in the mixing studies include pitot pressure, static pressure, and stagnation temperature at the exit plane of the mixing tube. Conventional pitot probes and long cone supersonic static probes are used for pressure measurements. The pitot tube is a flat-cut (1.3 mm outer diameter) tube with a 1 mm opening facing the flow. A long cone supersonic probe with four static holes of 0.35-mm-diam, 90 deg apart is used for measuring static pressure. The four symmetrically located orifices of the static probe are at 22 mm from the vertex of the cone. A diaphragm type transducer (with an accuracy of ±0.5%) is used for measuring pressures, which receives the pressure signals from the probes and processes them to a digital display unit. Temperature measurements are done using a calibrated Winkler-type total-temperature probe equipped with a Chromel–Alumel thermocouple. The probe has a radiation shield and the error caused by radiation has been estimated to be within 1.45%. A traversing mechanism is used to move the probes in radial and axial directions within the flowfield.

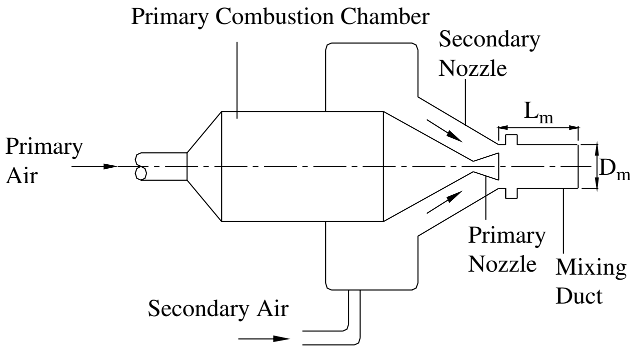


Fig. 1 Schematic Diagram of Experimental Setup.

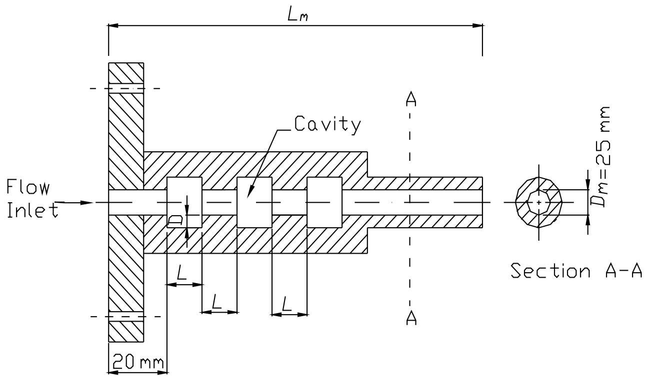


Fig. 2 Details of Mixing Tube.

III. Results and Discussion

A. Distribution of Stagnation Temperature

The emphasis on nonisothermal studies is the investigation of thermal mixing, which is characterized by the uniformity in temperature distribution. Because there exists a large difference in temperatures between the primary ($T_{o,\mathrm{pri}} = 1050$ K) and secondary jets ($T_{o,\mathrm{sec}} = 305$ K), an unmixed flow would be characterized by a nonuniform temperature distribution. The temperature will be higher near the axis when mixing is incomplete, as the hot primary jet issues closer to the axis. A more uniform stagnation temperature distribution in the flowfield indicates the enhancement in mixing of the two jets.

Figure 3 shows the radial distribution of T_o normalized by the stagnation temperature of the primary jet T_{oi} at various radial locations for three mixing tubes (L_m/D_m) for different cavity configurations. In the abscissa, r/R denotes the radial distance from the centerline, r, normalized by the radius of the mixing tube, R.

From Fig. 3a, it is observed that the stagnation temperature is high near the axis and reduces toward the wall of the mixing tube for both cavity and no-cavity configurations. This profile shows a nonuniform temperature distribution indicating poor mixing of the two jets. In other words, mixing of the coaxial jets is yet to begin at this mixing tube length. It is seen that the stagnation temperature profile tends to be flattened with increase in the cavity configurations. As the secondary flow passes over the cavity, the unstable shear layer of the secondary flow that emerges from the leading and trailing edges of the cavity interferes with the primary flowpath and induces mixing. Increase in the cavity configurations generates additional shock waves, which enhances mixing of the jets.

The temperature distribution tends to be flattened at the mixing tube length of $L_m/D_m = 4.2$ (Fig. 3b) and an almost uniform temperature profile is observed for the cavity configurations at the mixing tube length of $L_m/D_m = 5.0$ (Fig. 3c), showing better thermal mixing of the coaxial jets using cavities rather than no-cavity configurations. This observation of the cavity configurations arranged in tandem provides a more uniform temperature distribution in coaxial supersonic jets, and is an indication that it can be used in supersonic combustors.

B. Degree of Thermal Mixing

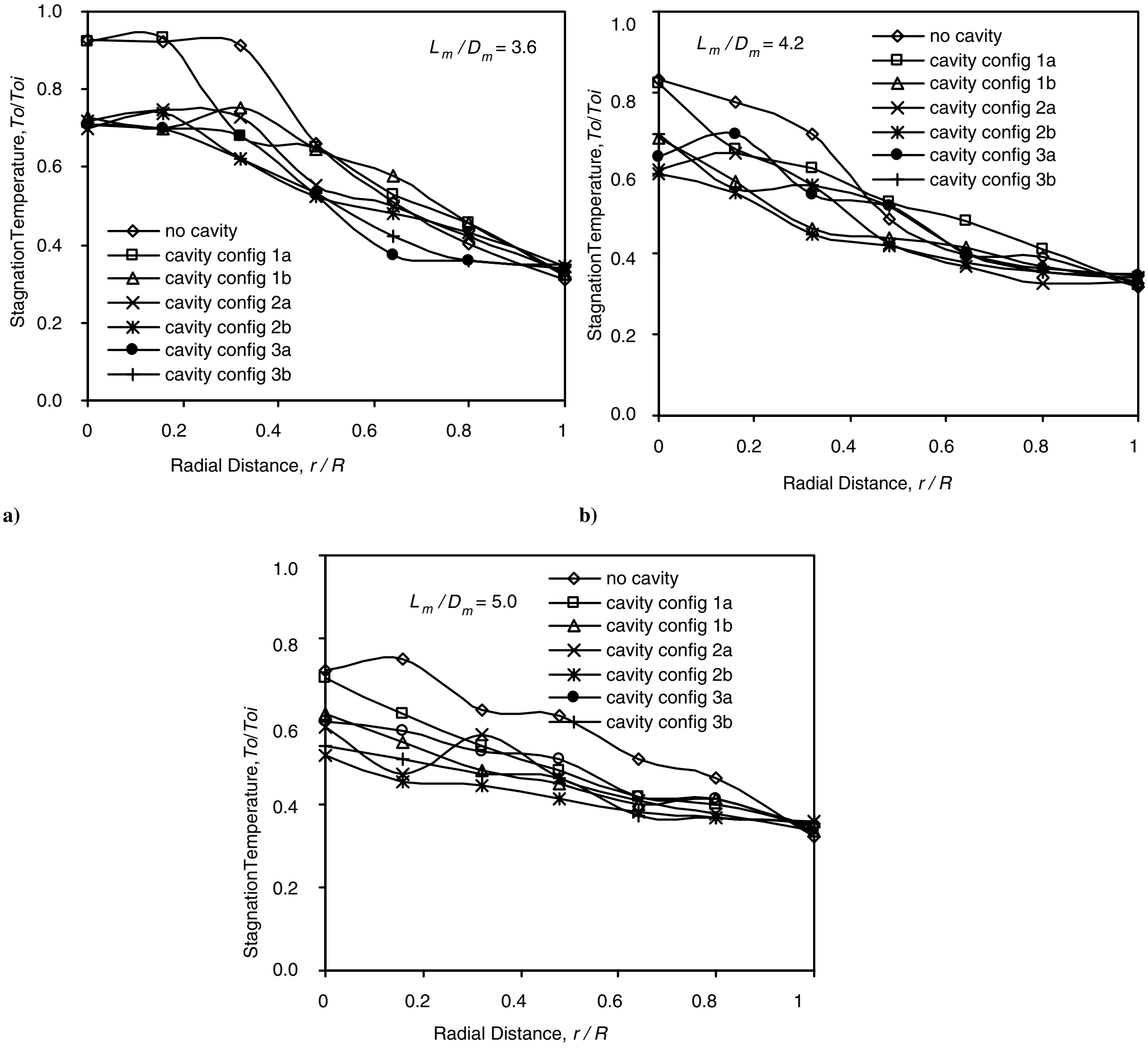
It is necessary to quantify the mixing performance of the cavities to optimize the configuration by defining a parameter called degree of thermal mixing [11] (DOT), which is a measure of the uniformity of the stagnation temperature at the exit radial plane of the mixing tube. A dimensionless parameter ϕ is defined as

$$\phi = 1 - (\sigma_{\propto}/ \propto_{\mathrm{av}})$$

where $\sigma_{\propto}$ denotes the standard deviation of the radial distribution of temperatures at the exit plane of the mixing tube. The denominator is the weighted average of the temperature distribution along a radial line at the same axial location. For a perfectly mixed flow, the distribution has to be uniform across the entire section. The uniformity factor is used to define DOT as

$$\mathrm{DOT} = \phi - \phi_{\mathrm{un}}/1 - \phi_{\mathrm{un}}$$

where ϕ_{un} represents the value of ϕ when the two streams are totally unmixed. This parameter shows a direct measure of the mixedness of the combined stream. When the two streams are completely mixed, DOT will be $\phi = 1$ and when they are totally unmixed $\phi = \phi_{\mathrm{un}}$, DOT will be equal to zero. Figure 4 shows the degree of thermal mixing at various axial distances of the mixing tube for the different cavity configurations. In all of these cases, the degree of mixing for the two jets in the presence of cavities is compared with that of the no-cavity case. It is seen from the plot that increase in the axial distance of the mixing tube increases the degree of thermal mixing due to the viscous forces inside the mixing tube that occurs due to increased surface area. For the no-cavity configuration, DOT has a value of



a)

b)

c)

Fig. 3 Radial Distribution of Stagnation Temperatures.

0.75 for the mixing tube with $L_m/D_m = 5.0$. Enhancement in mixing of the two jets is achieved by introducing cavities in the flowpath. It is also known [12] that the wall static pressure will rise due to the insertion of cavity configurations in the mixing tube and creates a drag force which moves upstream of the flow that weakens the shock waves emanating from the cavities. The plot indicates that cavity configuration 2 approaches a value of 0.89 and the cavity configuration 3 has a value of 0.78. The decrease in thermal mixing of cavity configuration 3 is due to higher drag force, which reduces the cavity assisted mixing of the jets. Further increase in the cavity configuration will reduce the mixing of the two jets.

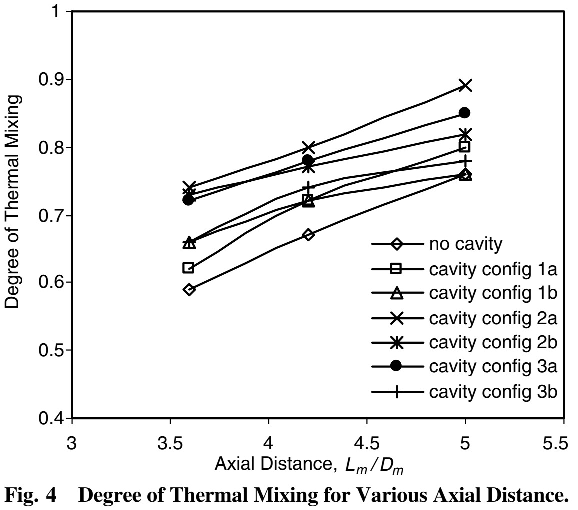


Fig. 4 Degree of Thermal Mixing for Various Axial Distance.

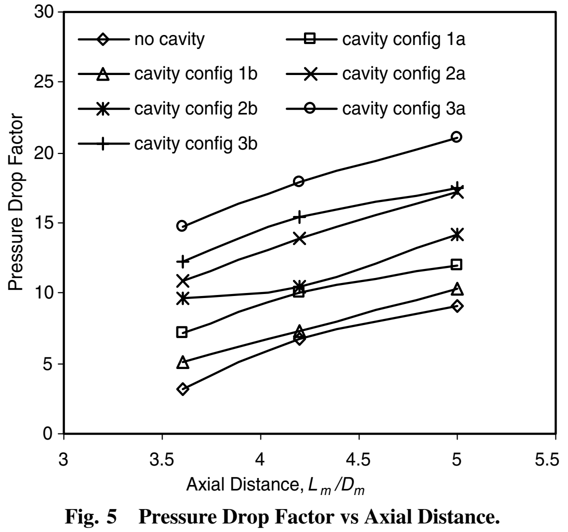


Fig. 5 Pressure Drop Factor vs Axial Distance.

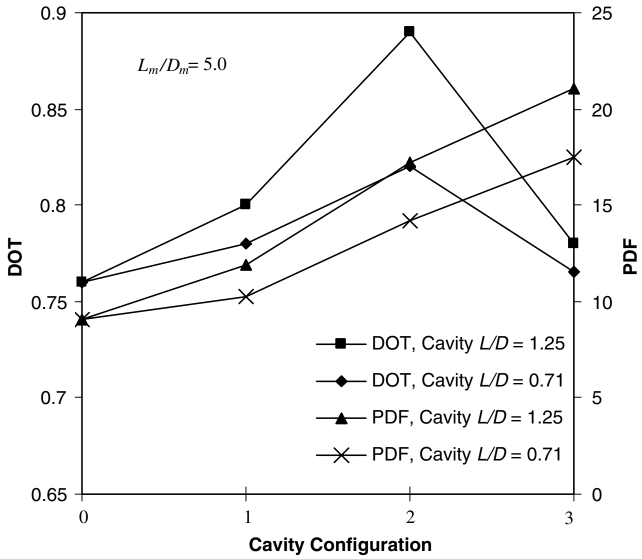


Fig. 6 Comparison of DOT and PDF for Various Cavity Configurations.

C. Stagnation Pressure Loss

It is also necessary to analyze the stagnation-pressure loss of the coaxial jets due to the mixing augmentation provided by the cavities. The stagnation-pressure loss is defined by a parameter called pressure drop factor (PDF), which is the difference between the weighted average stagnation pressures at the inlet, and the axial distance considered, normalized by the weighted average of the inlet stagnation pressures measured at the radial plane of the mixing tube. Figure 5 shows the pressure drop factor as a function of the axial distance of the mixing tube for the different cavity configurations. The plot reveals that the no-cavity case provides less stagnation-pressure loss than cavity configurations. The increase in the cavity configuration provides higher stagnation-pressure loss due to increased shock waves that arise from the cavities. It is also seen that increase in the axial length of the mixing tube increases the stagnation-pressure loss due to the viscous losses inside the mixing tube.

Figure 6 shows the comparison of the degree of thermal mixing with pressure drop factors for the different cavity configurations. It is seen from the plot that the general run of the curves is almost identical for both the cavities (i.e., $L/D = 1.25$ and 0.71). For both the cavities, the degree of thermal mixing enhances up to configuration 2 and reduces for the configuration 3 due to the higher drag forces, which affect the cavity-actuated mixing. The pressure drop factor increases linearly until cavity configuration 3 (Fig. 6) indicates that stagnation-pressure loss increases with enhancement in cavity configurations. From the preceding discussions, it is clear that cavity configuration 2 provides a more complete mixing of the two jets with less stagnation-pressure loss. Further addition of cavity configuration results in poor thermal mixing performance with higher stagnation-pressure loss. Though the experiments are conducted at lower Mach numbers than the actual flight conditions, the results are encouraging pointers for supersonic combustion applications.

IV. Conclusions

The experiment considers coaxial jets that enter into the mixing tube with different stagnation temperatures. Distribution of stagnation temperatures and pressures at the exit plane of the mixing tube are analyzed for various cavity configurations and are compared with the no-cavity case. A more uniform stagnation temperature distribution is observed for cavity configuration 2 for the mixing tube of $L_m/D_m = 5.0$. This reveals that better thermal mixing of the two jets occurs at this length, whereas for the no-cavity configuration the temperature distribution is not uniform. The quantitative analyses of the stagnation temperature distribution reveal that increase in the cavity configurations enhances thermal mixing of the two jets with higher stagnation-pressure loss than no-cavity configurations. A more complete thermal mixing is obtained by cavity configuration 2 with less stagnation-pressure loss than configuration 3. This is due to increase of wall static pressure in the mixing tube which affects cavity-assisted mixing with higher stagnation-pressure loss. The stagnation-pressure loss increases with poor mixing for further enhancement in the cavity configurations.

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R. Bowersox
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