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The Effect of Transverse Injection Upstream of an Axisymmetric Aft Wall Angled Cavity in a Supersonic Flow Field

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Abstract. Experiments are performed in a supersonic non-reacting flow facility to investigate the performance of an axisymmetric aft wall angled cavity with upstream fuel injection in a Mach 1.8 flow field. The supersonic combustor has a circular cross sectional duct in which cavities are introduced at a distance of 20 mm from the inlet. The aft wall of the cavity is tapered towards flow downstream and inclined with two step consecutive angles. Flush wall mounted injector is mounted at the upstream of the cavity. The tests are conducted at three fuel injection pressures to simulate the flow field in the present study. The mixing performance of the aft wall angled cavities are analysed based on the momentum flux distribution at the exit of the combustor and the stagnation pressure loss across the combustor and compared with the rectangular cavity. Transverse upstream injection of aft wall angled cavities enhances mixing than rectangular cavities, deliberated with less stagnation pressure loss from the former. Increase in injection pressures resulted in more uniform mixing across the flow direction of the combustor irrespective of the cavity configuration, concurrently induces more stagnation pressure loss due to increase in jet penetration depth into the main stream.

1. Introduction

Fuel injection system in supersonic flow necessitates the proper design in order to optimize the scramjet combustor efficiency [1]. The simplest method of fuel supply system is the normal injection [2] from the wall orifice of the combustor which creates a strong three dimensional shock waves during its interaction with the incoming supersonic flow. Due to the injection of jet with cross flow interaction of mainstream flow, subsonic vortex regime is formed around the jet base region [3] i.e. both the upstream and downstream region of the jet results in enhanced mixing. The cross flow mixing is established in two dimensional combustors which provides substantial stagnation pressures loss due to the formation of strong shock waves.

Many researchers [4-8] investigated the applicability of cavities in scramjet combustor in terms of mixing and flame holding. Transverse and angled fuel injection upstream of cavity in a Mach 2 flow is experimentally investigated by Gruber et al. [9], reported that the jet penetration increases with increase in injection pressure. In addition, the jet penetration rate is inversely proportional to the entrainment of fuel into the cavity. In-addition, the mixing is enhanced between shock boundary layer and jet interaction with increase in backpressure. Wang et al. [10] investigated the hydrogen jet interaction with cavity in a supersonic stream. A stable combustion is achieved by exposing the cavity in the supersonic flow field. Moreover, increase in injection pressure, pushes the flame upstream of the cavity due to stronger shear layer separation resulting from intense heat release and jet cavity shear layer interaction which increases the flame spread rate into the main stream. Cai et al. [11] showed that upstream fuel injection with rear wall cavity expansion provides a total pressure loss than without configuration. Moreover, stable flame is observed in the cavity region for shorter injection distance and further increase in injection distance upstream from the cavity provides a stable flame downstream of the cavity. Liu et al. [12] studied the effect of mixing characteristics of kerosene injection in a scramjet combustor under cold flow condition. The researchers reported that for higher injection pressures, the jet penetration depth increases into the main stream which could enhance the mixing.

The open literatures reported the effect of flush wall mounted fuel injector upstream with respect to cavities in a two dimensional supersonic combustor under non-reacting and reacting flow conditions. The present work focuses on the mixing performance of transverse injection upstream of an aft wall angled cavity in a circular cross sectional combustor. The bulk mixing performance is analyzed based on the wall static pressures along the flow direction, momentum flux distribution based on the static and total pressures at the exit of the combustor and the stagnation pressure loss across the combustor.

2. Details of Experiment

The performance of an axisymmetric aft wall cavity with upstream fuel injection is experimented in a non-reacting supersonic flow facility. The tests are performed at a flow Mach number of 1.8±0.05 in a circular cross sectional duct which acts as a supersonic combustor. The diameter and length of the combustor is 26mm and 95 mm respectively. The tests are carried out at an operating pressure of 0.58Mpa and temperature of 305K. A flush wall fuel injector of 1mm in diameter is mounted at a distance of 10mm from the inlet of the combustor. Three injection pressures of 7 bar, 7.5 bar and 8.0 bar are considered and compared with no injection case. Air is used as the injectant to stimulate the fuel in the non-reacting flow experiments. Axisymmetric open cavities are placed 10mm downstream of the injector. The cavities are of constant depth and base length. The aft wall of the cavity is inclined to two consecutive angles with the flow direction is shown in figure 2. The primary angle (θ_1) of the cavity is kept at 30 degrees and the secondary angle (θ_2) is varying at 15, 30, and 45 degrees which is listed in table 1. The schematic view of the supersonic combustor model is shown in figure 1.

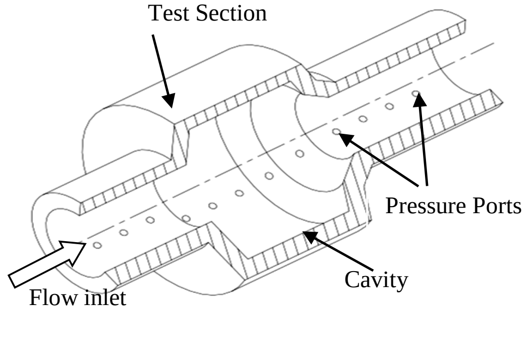

Figure 1. Schematic view of supersonic combustor

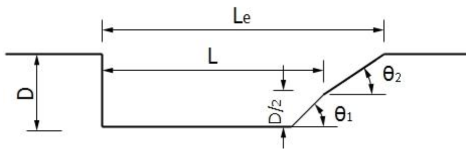

Figure 2. Details of cavity geometry

Table 1. Geometrical details of cavity configurations

Notation	Cavity L/D	Effective Le/D	Primary angle θ_1 (degree)	Secondary angle θ_2 (degree)
90,90	4	4.0	90	90
30,45	4.9	5.3	30	45
30,30	4.9	5.7	30	30
30,15	4.9	6.65	30	15

Static pressure ports of 1mm in diameter is located at the bottom wall of the combustor along the flow direction. The static pressures are measured using a scanning type pressure transducer (Scanivalve, Model: DSA3218, range: 0 to 1725 kPa, accuracy: ±0.5%) and processed through a Lab view program. The experiments are accomplished three times under identical working conditions for each tests to ensure the repeatability. A long cone supersonic static and pitot stagnation probes are employed at the combustor exit to measure the radial pressure distributions. The uncertainty in the pressure measurements of the present experiment is estimated to be less than ± 2%.

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3. Results and Discussion

3.1 *Static Pressure Distribution*

Figure 3. shows the wall static pressure values at different axial locations (x/Lc) for three injection pressures of different cavity configuration and compared with no injection case. In the plot 'x' denotes the static pressure port location from the inlet to the total length 'Lc' of the combustor. In case of no injection [5], the static pressure increases at the cavity region due to separation and reattachment of shear layer at the leading and trailing edges of the rectangular cavity. As the aft wall secondary angle (θ_2) of the cavity reduces from 90 degree to 15 degrees, static pressure at the cavity base reduces due to more entrainment of fluid into the cavity and shows a peak value at the slant aft wall of the cavity due to strong shock waves resulting from reattachment of shear layers which is due to the formation stable flow field above the cavity region, as observed [13]. In case of transverse injection as illustrated in figure 3, a static pressure values are higher at x/Lc=0.16 due to upstream wall boundary layer separation, creates a subsonic region for mixing of fuel and air at the injection location [14]. The static pressure profile downstream of the injector location also exhibits similar profile with no injection case with higher values indicates an increase in entrainment rate of the flow into the cavity.

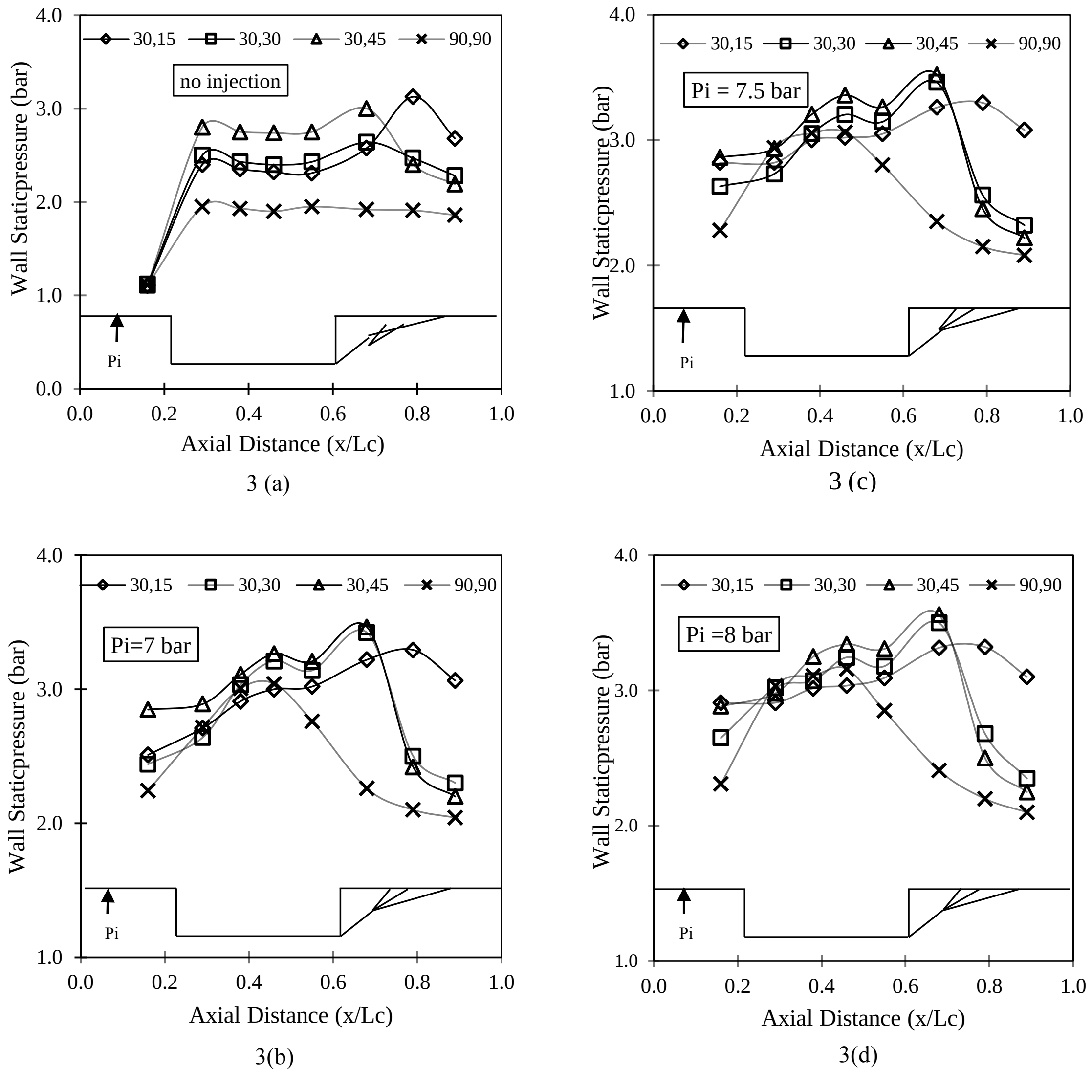

Figure 3. Static Pressure Distribution for Various Upstream Injection Pressures in Aft Wall Angled Cavities

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As the aft wall angle (θ_2) of the cavity reduced from 90 to 15 degrees, the static pressure value is high at the aft wall due to reattachment of shear layers which spans over the entire length of the aft wall which creates a compressive zone in the region. Increment of injection pressures from 7 bar to 8bar increase the wall static pressure values along the axial direction of flow. Flow visualization studies could not be established to visualize the flow pattern due to circular cross sectional combustor. Based on the open literatures in the two dimensional combustors, it is believed that the flow pattern follows the similar array with the two dimensional aft wall angled cavities [13].

3.2 Momentum flux distribution

The qualitative mixing performance of the transverse injection into the core flow is analysed based on momentum flux distribution at the exit plane of the combustor. The momentum flux (MF) values are calculated based on the following equation,

$$\mu = p\,(1+\gamma M^2) \qquad (1)$$

In the equation, the static pressures and Mach numbers are calculated based on the measured values of static and stagnation pressures using Rayleigh pitot formula. In an axisymmetric combustor, momentum flux value is higher at the centre due to higher operating pressure than at the wall of the combustor. The constant momentum flux profile normal to the axial direction of the flow indicates a uniform mixing across the combustor which is necessary for combustion processes.

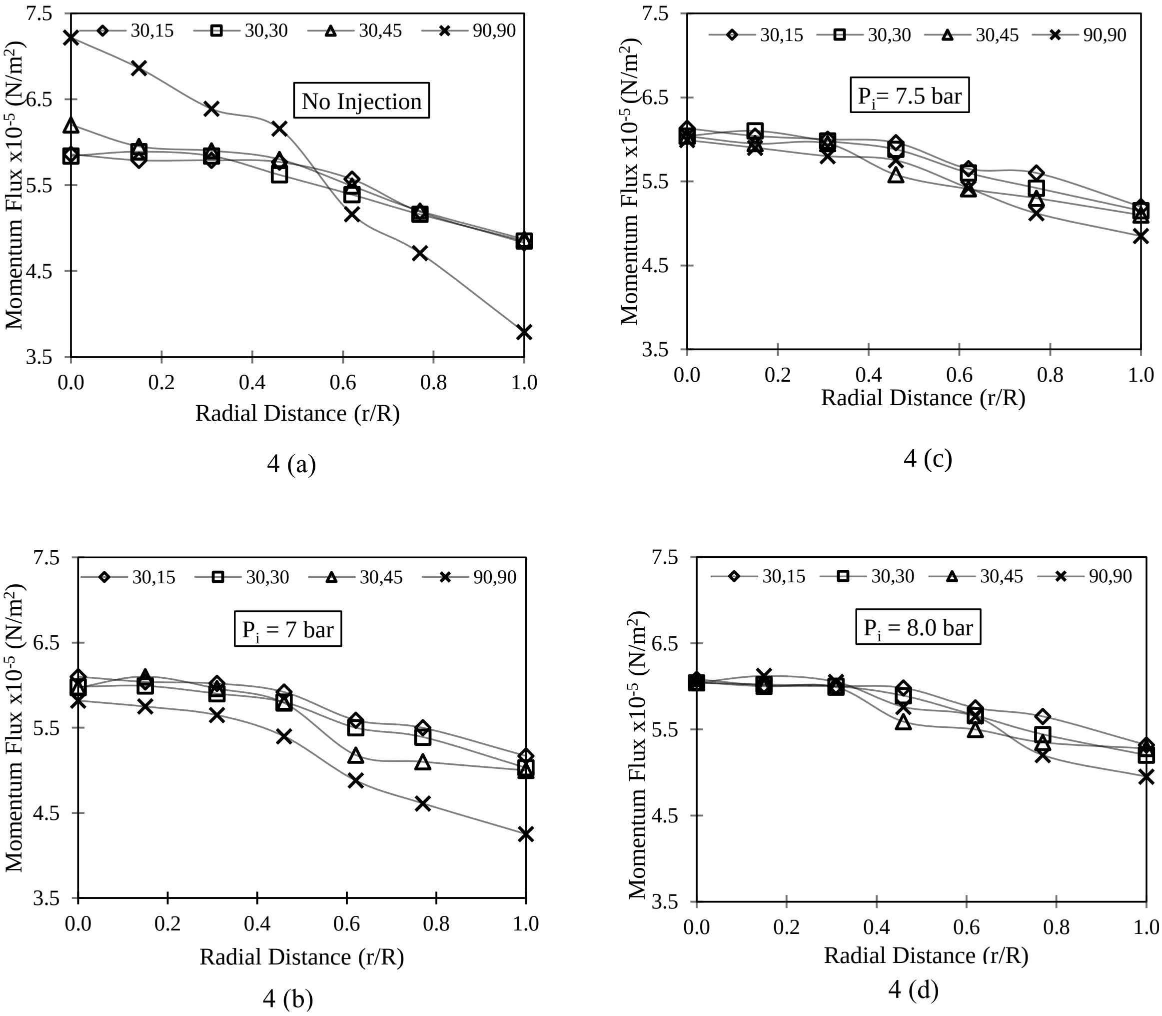

Figure 4. Momentum flux Profile for Various Upstream Injection Pressures in Aft Wall Angled Cavities

Figure 4 shows the momentum flux distribution of cavities for varying injection pressures and compared with no injection. In case of no injection [5] (fig4.a), for rectangular cavity, the momentum flux value is high at the centre and low near the wall of the combustor indicates a non-uniform mixing of the flow. As the primary aft wall angle (θ_1) of the cavity is reduced to 30 degrees, the MF value is decreased at the centre and increases near the wall due to shear layer separation and reattachment from the aft wall of the cavity which enhances uniform mixing.

It can be observed from the Figure 4(b) that the transverse injection changes the MF profile more uniform for all the cavity configurations. For rectangular cavity (90, 90), a sudden change in the MF profile is observed due to jet penetration into the main stream which creates a subsonic region over the cavity and downstream enhances mixing of the flow. For the cavity with aft wall angle of (θ_1)30 degrees, the MF distribution is more uniform with decrease in the secondary aft wall angle (θ_2) from 45 degrees to 15 degrees. Increase in injection pressures as represented in Figures 4(c) and 4(d) that provides a uniform MF profile irrespective of cavity configurations with marginal increase in the MF values.

3.*3 Stagnation Pressure loss*

Enhancement in mixing using cavities with transverse injection provides a uniform mixing profile, it is necessary to analyse the stagnation pressure loss incurred due to the shock waves emerges from the cavity and transverse injection. The loss in stagnation pressures across the combustor is calculated based on the difference in stagnation pressures at the inlet to exit of the combustor to the inlet stagnation pressure. The stagnation pressure loss for no injection and injection conditions are plotted and compared with rectangular cavity (90, 90) for various secondary aft wall angled cavities as shown in figure 5. From the plot, it is noticed that aft wall angled cavities for θ_2 at 30 degrees provide less stagnation pressure loss of about ~8% which indicates a stable flow field above the cavity region than rectangular cavity. Increase in injection pressure increases the stagnation pressure loss due to increment in jet penetration depth into the core flow resulting in strong shock waves.

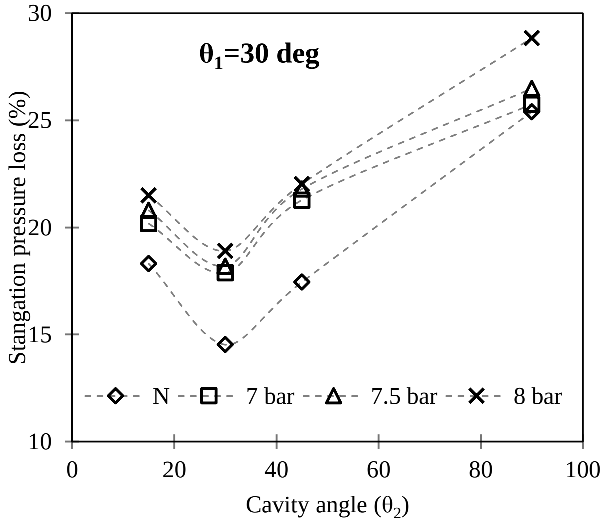

Figure 5. Stagnation pressure loss for different cavity configurations with varying injection pressures

4. Conclusion

The effect of aft wall angled cavities with upstream transverse injection in a non-reacting Mach 1.8 axisymmetric flow field is experimentally investigated. The axisymmetric cavities are mounted inside a cylindrical duct which acts as the supersonic combustor. Aft wall of the cavity is inclined with two step consecutive angles. Flush wall mounted fuel injector is located upstream of the cavity. Air is used as the inject ant to stimulate fuel for the non-reacting flow conditions. Three injection pressures are considered to investigate

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the bulk mixing characteristics of the flow using cavities and compared with rectangular cavity. Transverse injection into the main stream creates a strong shock waves and also resulted the increase in the static pressure values around the jet base region and downstream of the cavity. Upstream injection of aft wall angled cavity provides less static pressure profile which indicates a more stable flow field than rectangular cavity. The improvement in mixing uniformity is observed for increase in injection pressures irrespective of cavity configuration with marginal variation. Stagnation pressure loss increases with increase in injection pressures due to increased jet penetration depth which causes strong shock wave in the flow main stream. Double aft wall cavity with lower angles provide less stagnation pressure loss of about ~8% and uniform mixing than rectangular cavity which is suitable for supersonic combustion applications.

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