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Effect of cavity fore wall modifications in supersonic flow

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Abstract. Understanding the complex behaviour of the cavity flow is essential for the design of supersonic combustor. The characteristics of the axisymmetric aft ramp cavity with fore wall modification have been experimentally studied in a blow-down type supersonic flow facility. The facility consists of a conventional CD nozzle that issues a flow Mach number of 1.88 to a supersonic combustor of circular cross section, which is placed immediately downstream of the nozzle. The axisymmetric cavities are incorporated within the combustor. The cavities are of open type and their length is kept constant while their depth varies. The aft wall of the cavities is inclined with three ramp angles and the fore wall is provided with a constant fillet radius of 3 mm. The performance of the cavity is analysed based on wall static pressures, momentum flux distribution at the exit of the combustor and stagnation pressure loss across the combustor. The study reveals that fore wall fillet cavities provide less cavity drag and stagnation pressure loss for various aft ramp angles under identical operating conditions.

1. Introduction

Cavity is considered as one of the potential devices for mixing enhancement and also effective flame holding in scramjet engine combustor [1–6] because of the generation of less drag than other active devices like struts [7, 8] and pylons [9]. The cavity flow has been studied in the past for applications in wheel wells, aircraft weapon bays, scramjet combustors, etc. The renewed interest in the cavity flow is due to the complexity of flow field within it. Researchers have characterized the cavities based on the shear layer reattachment as either open or closed. In case of open cavity, the separated shear layer from the leading edge of the cavity reattaches at the aft wall. On the other hand, for closed cavity, the shear layer reattaches at the bottom wall of the cavity and this creates higher drag than open cavity. Even though the flow over the cavity is supersonic, the shear layer regime within the cavity is subsonic. The shear layer is unstable in subsonic regime and a small pressure disturbance in the shear layer causes pressure coupled feedback mechanism [10], which triggers a periodic vortex shedding that leads to the acoustic oscillations of the fluid stream. Open cavities are desirable for scramjet applications as they impose smaller drag penalty on the flow.

An experimental study by Yu *et al.* [6] on cavities in a Mach 2 reacting flow field has reported that flame holding is achieved by smaller aspect ratios than the longer one. In addition, the multiple cavity configurations provide an effective flame holding than the single cavity. Chung [11] investigated the characteristics of a rectangular cavity in supersonic flow field based on cavity geometry and Mach number of the flow. Kang *et al.* [12] studied the effect of zigzag cavity in Mach 2.5 flow as compared



to a plain cavity. They observed that zigzag cavity generated transverse oscillations, which enhanced combustion within shortened combustor than plain cavity. Experimental and computational studies on different aft wall angles and off-set ratios of the cavities in a supersonic flow indicated that stable flow was achieved by decreasing the aft wall angle below 90 degrees [3]. Similar observations were found for varying cavity aft wall angles below 90 degree in a supersonic flow field [13, 14].

The above mentioned investigations are based on rectangular cavities in a 2D supersonic flow with and without cavity aft wall angle. Moreover, literatures on axisymmetric cavity flow are scant. In an on-going research, the features of axisymmetric cavity configurations for scramjet combustor have been reported [15]. The objective of this study is to investigate the performance of axisymmetric fore wall fillet cavities in a Mach 1.88 flow. The investigation on wall static pressures, momentum flux distribution at the exit of the combustor and stagnation pressure loss associated with the flow across the combustor are estimated for improving the scramjet combustor performance.

2. Experimental setup

A blow-down type supersonic flow facility is used in this study for the non-reacting flow experiments. The facility was consisted of a CD nozzle, followed by a circular cross sectional duct that acted as a supersonic combustor. The nozzle issued a flow Mach number of 1.8. The operating condition of the experiment is shown in Table 1. The supersonic combustor was of 26 mm in diameter and 95 mm in length. Cavities were incorporated at a distance of 30mm from the inlet of the combustor. Sectional view along the flow direction of the combustor is shown in Figure 1. The cavities were of open type and axisymmetric, with constant length, L but varying depths, D . The cavity details are illustrated in Figure 2. The aft wall of the cavity was inclined to three different angles: 15, 20 and 30 degrees with the horizontal direction. A fillet radius of 3mm was provided at the fore wall of the cavity for "with fillet cavity" configurations. Table 2 shows the geometric dimensions of the cavity used for this study.

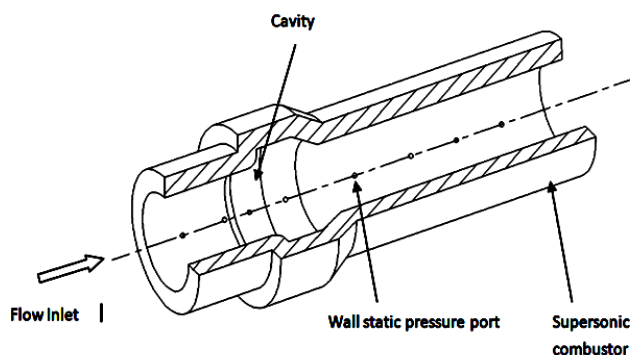


Figure 1. Schematic diagram of supersonic combustor

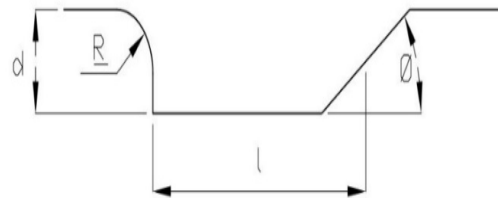


Figure 2. Schematic diagram of cavity layout

Table 1. Operating conditions of supersonic combustor

Parameters	Values
Stagnation pressure	800Kpa
Static pressure	110Kpa
Stagnation temperature	300K
Mach number	1.8
Mass flow rate of air	0.2 kg/s

Table 2. Geometrical information of cavity configuration

Cavity configuration	Length, L (mm)	Depth, D (mm)	L/D	Ramp angle, °
WF3015	15	3	5	15
WF4015	15	4	3.75	15
WF5015	15	5	3	15
WF3020	15	3	5	20
WF4020	15	4	3.75	20
WF5020	15	5	3	20
WF3030	15	3	5	30
WF4030	15	4	3.75	30
WF5030	15	5	3	30

The static pressure distribution along the axial length of the combustor was measured using 1-mm diameter ports that were placed along the combustor wall in the flow direction. Nine pressure taps were equipped along the combustor walls to acquire pressure data along the flow direction. In addition, a long cone static and pitot pressure probes were used to measure static and stagnation pressures at the exit of the combustor to examine the flow characteristics influenced by the cavities. Each experiment was executed three times for repeatability. The uncertainties were estimated to be less than 3% for the pressure measurements. The probes were moved in the radial direction of the flow field by a traversing mechanism.

3. Results and Discussion

3.1. Wall static pressure distribution

The surface static pressures along the axial length of the flow for various aft ramp angles of with and without fillet cavities are plotted in Figure 3 and Figure 4. In the plots, wall static pressure (P_w) to the inlet static pressure (P_i) of the combustor is normalized to the non-dimensional axial length (x/L) of the combustor. The 'x' denotes axial distance of the probe measured from the inlet of the combustor and L denotes the total length of the combustor. WF denotes cavity with fillet, third numeral denotes the depth of the cavity whereas the cavity ramp angles are mentioned as $\theta 15$, $\theta 20$ and $\theta 30$. The fillet radius, R of 3 mm was used for all the tests. The cavity without fillet is mentioned as WOF. In Figure 3a, a uniform wall static pressure profile is observed for no cavity over the entire length of combustor. For cavity aft ramp angle $\theta 15$ (Figure 3a), a rise in static pressure is seen at the leading edge of the cavity than the free stream pressure due to the shear layer separation, which led to a compression zone. The separated shear layer reattached at aft ramp of the cavity, resulting in increased static pressure.

The static pressure over the cavity region decreased with increase in aft ramp angle from 15 to 30 degrees of the cavity. A study on 2D flow over rectangular cavity by Gruber *et al.* [1] revealed that a decrease in aft ramp angle will reduce the static pressure at the bottom wall but will increase it at the reattachment region, i.e. at the aft ramp of the cavity. Moreover, the schlieren pictures revealed that the flow became stable in the cavity region by reducing the cavity aft ramp angle. A stable flow field with continuous source of radicals to stabilize the flame is essential for a good flame holder. In the present study, the flow visualization techniques cannot be implemented due to the selected cross section of the combustor. Higher static pressure was observed for $\theta 15$ and $\theta 20$ degrees due to the shock reflections that emerged from the cavity leading edge. A uniform static pressure profile was observed for $\theta 30$ in the cavity region. Similar trend was observed for the fillet cavities (see Figure 4a), with a marginal decrease in the static pressure profile at the leading edge of the cavity, indicating that cavity drag was slightly reduced by the fore wall fillet cavity.

In case of cavity with 4 mm depth (see Figure 3b), the static pressure at the leading edge of the cavity was less than 3 mm cavity depth (see Figure 3a) and this implies that the increase in depth of the cavity leads to an expansion zone. At $x/L = 0.5$, the static pressure has more value and this indicates that a stronger reattachment of shear layers at the cavity aft ramp. For fillet cavities (see Figure 4b), the flow at the cavity leading edge is expansive in nature and showing less static pressure. It has a peak value at $x/L = 0.39$, indicating that reattachment of shear layers occurred at the base of the aft wall that increased the entrainment rate of the flow within the cavity. Further increase in depth of the cavity led to decrease in static pressure profile for all cavity with (see Figure 4c) and without fillet (see Figure 3c) configurations. A reduction in wall static pressure values is observed in the cavity region for fore wall fillet cavities, which indicates less cavity drag than without fillet cavities. In case of without fillet cavities, the shear layer reattached at the aft wall of the cavity. In contrast, the reattachment occurred towards the bottom wall corner of the cavity for fillet cavities, which increased the entrainment rate of flow in the cavity and enhanced the recirculation within the cavity regime, making it more competent for flame holding in scramjet combustors.

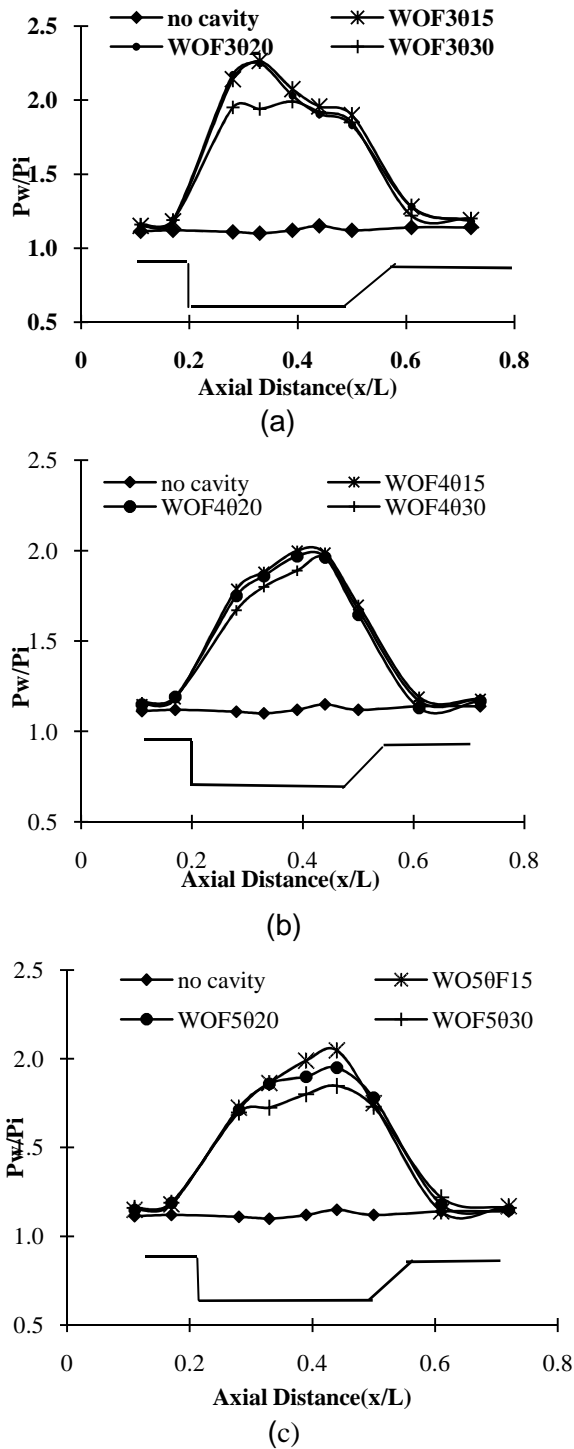


Figure 3. Wall static pressure profile of without fillet cavity for various aft ramp angles

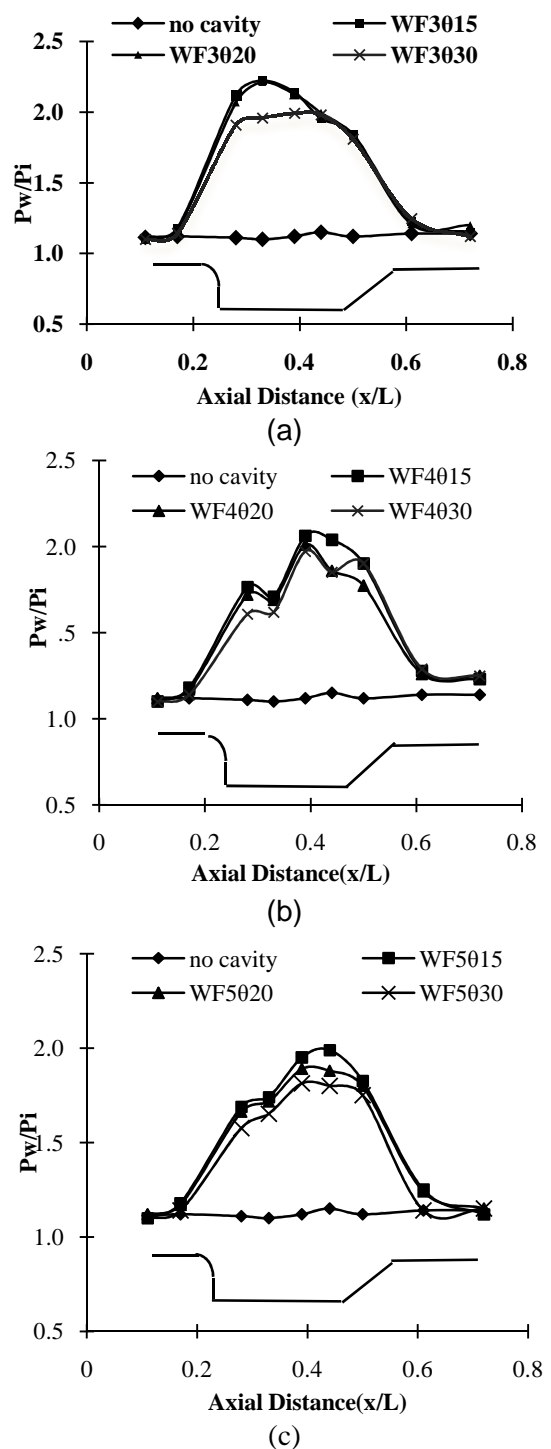


Figure 4. Wall static pressure profile of with fillet cavity for various aft ramp angles

3.2. Momentum flux distribution

The momentum flux distribution at the exit of the supersonic combustor in the radial direction is a measure of the extent of bulk mixing. The momentum flux is calculated as in Equation 1.

$$\mu = p (1 + \gamma M^2) \tag{1}$$

where p is the measured value of static pressure and Mach number, M is calculated from the measured values of static and stagnation pressures using Rayleigh-Pitot formula.

The momentum flux values for various cavity configurations at different radial distances at the exit of the combustor are depicted in Figure 5. In the plot, r/R denotes radial distance from the axis, r normalized by the radius, R of the supersonic combustor. Experimental results are presented for all cavity configurations operating under identical conditions and are compared with no cavity case. The momentum flux distribution was almost uniform for all cavity configuration compared to no cavity. In the case of no cavity, the momentum mixing was not uniform and it was showing poor mixing along the radial direction of the flow. For cavity configuration, the nature of the curve tended to be uniform from the centre towards the wall of the combustor. It was also observed that increasing the cavity ramp angle from 15 to 30 degrees would increase the momentum flux values at the combustor exit along the radial direction. A uniform momentum flux distribution from the center of the combustor till r/R of 0.8 was observed for fore wall fillet cavities, showing uniform mixing were provided by the fore wall fillet cavities.

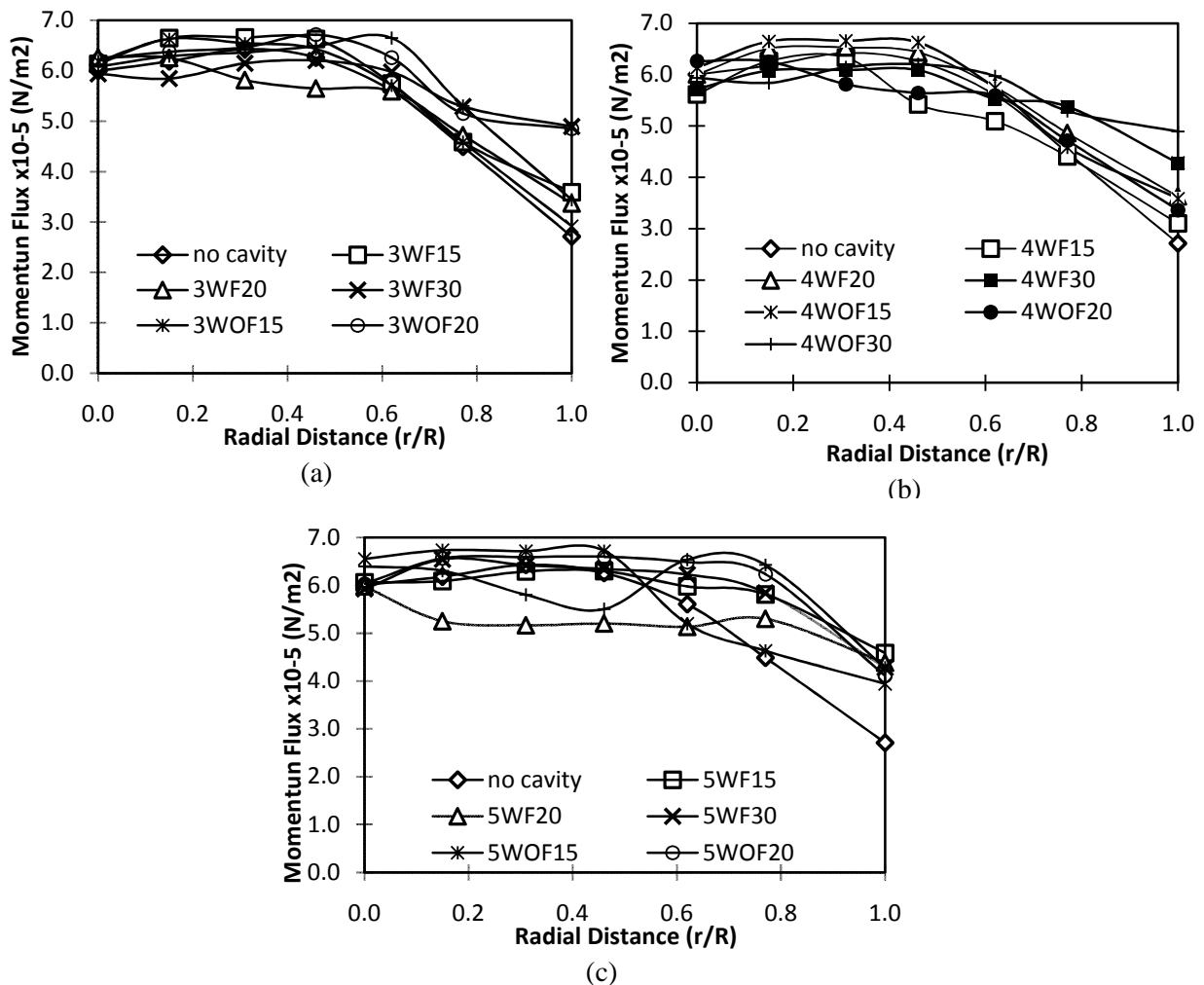


Figure 5. Radial distribution of momentum flux for various cavity configurations

3.3. Stagnation pressure loss

Stagnation pressure loss across the combustor is defined as the difference in stagnation pressures at the considered inlet and axial distance, normalized by the inlet stagnation pressure measured at the exit sections of the combustor along the radial direction. The change in stagnation pressure loss for various cavity configurations is shown in Figure 6. The stagnation pressure loss for no cavity was calculated to be 11%. From the plot, it is observed that with fillet cavities provided less stagnation pressure loss than without fillet cavity for all aft ramp angles. Moreover, increase in aft ramp angle increased the stagnation pressure loss due to stronger recompression of shear layers, which created a compressive zone downstream of the cavity. The strength of the shock waves emanating from the leading edge of the without fillet cavities was stronger than that of fillet cavities, which obstructed the main stream and increased the stagnation pressure loss. Fore wall fillet cavity of 4 mm depth and 15 degree ramp angle provided less stagnation pressure loss than other cavity aft ramp angles. From the observation, the fore wall fillet cavities of selected geometric dimensions will enhance fluid entrainment inside the cavity from the main stream. This leads to better mixing enhancement with marginal increase in stagnation pressure loss compared to cavity without fore wall fillet for varying cavity ramp angles.

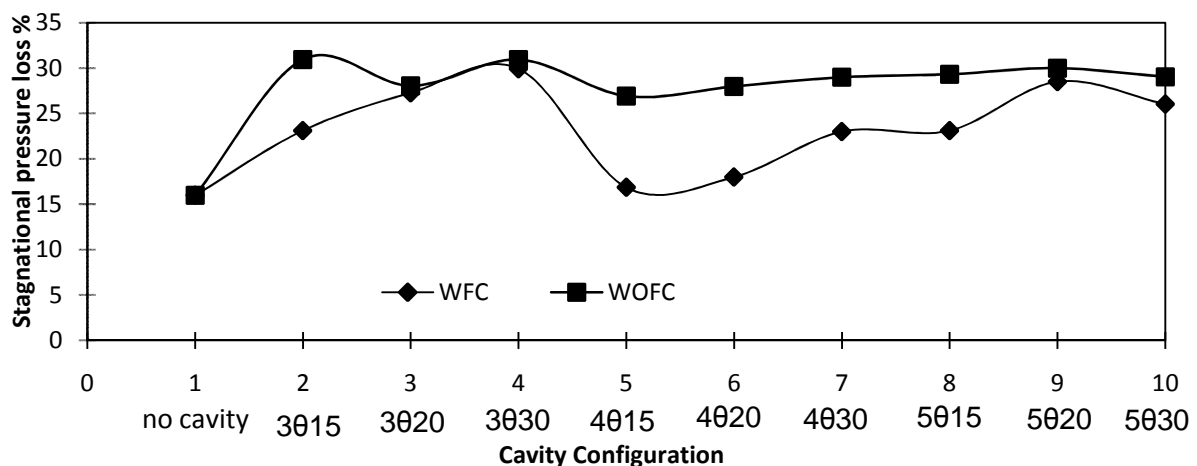


Figure 6. Stagnation pressure loss for with and without fillet cavities

4. Conclusion

The experiments were carried out in a blow-down type non-reacting supersonic flow facility, which can maintain a flow Mach number of 1.8 with an operating pressure of 0.7 MPa and at atmospheric temperature. Aft ramp cavities with constant fillet dimension at the fore wall were used for this study. In case of fore wall fillet cavities, the shear layer reattached at the aft wall bottom corner of the cavity, which increased the entrainment of the flow into the cavity and also enhanced the mixing of the flow. Decreasing aft ramp angle increased the static pressure profile due to stronger reattachment of the shear layer at the aft wall of the cavity. Increase in depth of the cavity decreased the static pressure profile for varying aft ramp angles. Momentum flux profile proved that fillet cavities provided uniform momentum mixing than without fillet cavities. Fore wall fillet cavities provided marginal variation in stagnation pressure loss than without fillet cavities. From the results, it is evident that fore wall fillet cavities with lower aft ramp angles can provide good mixing along with less stagnation pressure loss than without fillet cavities. Hence they are suitable as a potential flame holding device in scramjet combustors.

Acknowledgments

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