ISSN (Online) : 2319 - 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

Volume 3, Special Issue 3, March 2014

2014 International Conference on Innovations in Engineering and Technology (ICIET'14)

On 21st&22nd March Organized by

K.L.N. College of Engineering and Technology, Madurai, Tamil Nadu, India

Experimental Investigations on the Characteristics of Supersonic Flow past Axisymmetric AFT Ramp Cavities

Jeyakumar S, Surjith N, Venkateshwaran V, Karkuvelraja A, Samy G.S, Jaganathan K.D

Dept. of Mechanical Engineering, Kalasalingam University, Krishnankoil, Tamilnadu, India

ABSTRACT - The effect of axisymmetric aft ramp cavities in supersonic stream was investigated in a blow down type supersonic flow facility. The facility provides a supersonic flow of Mach 1.3 with a total pressure of 0.3MPa at a total temperature of 300K. Various fillet dimensions were made at the fore wall of the cavity and compared with absence of fore wall fillet cavities. The performance of the cavities was investigated using wall static pressures, static, and stagnation pressure measurements. Aft ramp cavity with fillet shows significant improvement in mixing and less stagnation pressure loss than that of the domain without fillet cavities.

KEYWORDS - Cavity flow, Supersonic flows, aft ramp cavities.

I. INTRODUCTION

Fuel injection, mixing and combustion of air and fuel and the flame holding are the fundamental key points of Scramjet technology. Many researchers for practical use posted various injection and flame-holding configurations. One of such many simple methods is to transverse the fuel injection into the combustor. This method leads the fuel jet to interrupt with the supersonic cross flow and results in formation of a bow shock in front of the injector. A modified transverse injection scheme is the dual injection system which has higher mixing rate and more total pressure loss than a single injection[1,2]. Use of a backward facing step downstream of the injector helps to ignite the air fuel mixture and generates a large subsonic recirculation region which has hot gases near the fuel air interface. This configuration leads to higher total pressure loss and increased pressure drag due to low pressure at the backward facing step.

In recent years, transverse injection of fuel upstream the cavity is found to have a significant improvement in hydrocarbon combustion efficiency[3-4]. Wall mounted cavities are characterized as either open or closed. The basic aspect of flow over cavity is the separation of boundary layer at the leading edge to form a free shear layer. The separated shear layer may reattach either to the base of the cavity or to the aft edge of the cavity wall depending on the parameters such as the cavity geometry, free stream Mach number, Reynolds number, and approaching boundary flow conditions. The cavity of the former type is termed as closed cavity (figure 2) and the latter one is referred as open cavity (figure 1). The downstream flow field of closed cavities is unsteady in nature. In general, a cavity becomes unsteady when $L/D \leq 10$. In the case of open cavity, the free shear layer formed at the leading edge of the cavity is in a subsonic layer even when the outer flow is supersonic. Since the flow is subsonic, the shear layer is quite unstable and it quickly rolls up to form a vortex. The small pressure disturbances in the unstable shear layer initially moves downstream but gets reflected from the trailing edge and thus comes back to the leading edge and causes vortex shedding. Thus the pressure coupled feedback mechanism triggers a periodic vortex shedding and causes acoustic oscillations of fluid stream nature, whose frequency depends on the L/D ratio of the cavity and the free stream Mach number. Open cavities are desirable for scramjet applications, as they impose smaller drag penalty on the flow.

Ben-Yakar and Hanson[3] revealed that cavities of specific dimensions kept in a supersonic flow provide effective flame holding capability and mixing enhancement with minimum total pressure loss. Yu and Shadow[5] conducted experiments on the enhancement of mixing in free jet by a cavity mounted at the exit of a supersonic nozzle. The cavities were two dimensional as well as semi annular of rectangular cross-section. Their results revealed that enhancement in mixing were achieved when the cavities were tuned to certain acoustic mode.

Yu et al[6] 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. Experimental studies[7] on cavities containing a Mach 2 open flame with angled injection showed that the cavities with a short aspect ratio provide good flame holding, whereas with relatively long aspect ratio shortened the flame length substantially via acoustic excitation.

Zhuang[8] experimented in a Mach 2.0 flow over a three-dimensional cavity. Large-scale structures in the cavity shear layer and visible disturbances inside the cavity were observed. A large recirculation zone and high-speed reverse flow was also seen in the cavity. In addition, supersonic microjets were used at the leading edge to suppress flow unsteadiness within the cavity. The microjet injection also modified the cavity mixing layer and resulted in a significant reduction in the flow unsteadiness inside the cavity. Direct injection[9] of methane and ethylene into the cavity with different aspect ratio having aft wall ramp revealed the effect of flame blowout limits depends on airflow rates, injection location, fuel type and cavity geometry.

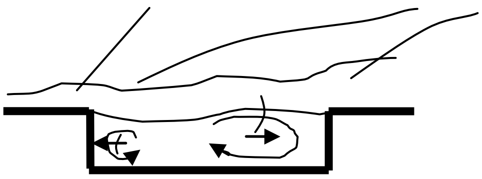


Figure 1 Open Cavity Flow

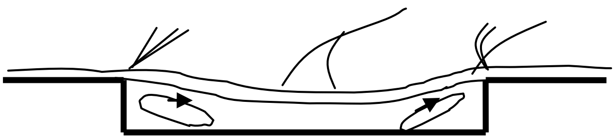


Figure 2 Closed Cavity Flow

Experimental and numerical investigation of ethylene-fueled recessed cavity flame holders were carried out by Kuo-Cheng Lin et al[10] and Gruber et al[11]. With transverse and direct injection of fuel, significant variation in the shape and spatial distribution of the cavity flame were observed at various fuel flow rates. Ming-Bo Sun et al[12] investigated on flame characteristics in supersonic combustor with hydrogen injected upstream of the cavity. OH radical distribution of the combustor flow field was observed using OH planar laser induced fluorescence. Their results showed that the cavity shear layer plays an important role in the flame holding process.

Yu[a] et al[13] investigated on Mach 2.5 flow, flame characteristics in supersonic combustor with different integrated kerosene fuel injector/flame holder cavity modules. Pure liquid or effervescent atomization in the supersonic combustor was visualized via Schlieren images and flame holding mechanism of the integrated cavity module was examined by OH PLIF measurements. Their result revealed the existence of a localized high-temperature reaction zone within the cavity.

Kim et al[14] investigated numerically concerning the combustion enhancement when a cavity was used for the hydrogen fuel injection through a transverse slot nozzle into a supersonic hot air stream. Several inclined cavities with various aft wall angle, offset ratio and length were evaluated for reactive flow characteristics. The combustor with cavity was found to enhance mixing and combustion at the same time and also increases the total pressure loss when compared with that of without the cavity. But, it was observed that there exists an appropriate length of cavity for enhancing the combustion efficiency and total pressure loss. Eunju et al[15] investigated on angled injection of hydrogen upstream of the cavity in a supersonic flow path. Their results showed that heat release due to combustion was mostly initiated by the shock wave from the cavity's trailing face and the ignition above the cavity does not have a strong influence on downstream combustion.

Hsu et al[16] conducted experiments using ethylene to measure quantitative fuel distribution around a cavity which was injected upstream of the cavity in a non-reacting Mach 2 flow at different back pressures to simulate static pressure rise due to combustion. They showed that the fuel be delivered directly into the cavity to eliminate the potential transition problem resulting from boundary layer behavior. Mohammed Ali and Job Kurian[17] conducted experiments on supersonic flow past cavities with varying ramp angles of fuel injection. Their focus was on the stability of the internal flow field and fluid entrainment into the cavity for different aspect ratios and different fuel injection locations. Unsteady and steady pressure measurements inside the cavity were the diagnostic methods used in this study.

Adam Quick et al [18] conducted experiments on the flow field associated with three upstream direct injection acoustic resonance cavities coupled with a previously designed downstream combustion cavity in a non-reacting flow were described. All the upstream mixing cavities were acoustically open with Length to Depth (L/D) ratio of order 1, and the downstream combustion cavity had L/D ratio of 4.7 with aft ramp angle of 25°. The three upstream mixing cavities were characterized in Mach 2. Free stream flow with injection at three different locations (Upstream wall, Centre and Downstream wall) within each cavity. The results revealed that injection at the upstream wall of the cavity provided greater penetration height into the free stream as well as faster mixing with the free stream compared with injection at the center or at downstream wall of the cavity. The objective of the study was to investigate the wall static pressure distribution and stagnation pressure loss of the supersonic jet with the aid of fore wall fillet aft ramp cavity configurations. The absence of fillet cavity configuration, Wall static pressures, Pitot and static pressures were noted at the combustor while observing the characteristics of the flow.

II. EXPERIMENTAL SETUP

The experiments were carried out in a blow-down supersonic test facility shown in figure 3. The test facility consists of a conventional convergent divergent nozzle designed for a flow Mach number of 1.3 with a total pressure of 0.3MPa at a total temperature of 300K. A supersonic combustor, 26mm in diameter and 130mm in length, was attached at the exit of the nozzle. The inflow conditions of the scramjet combustor were stated in Table1. Cavities were placed inside the combustor at a distance of 30mm from the inlet. The Schematic diagram of cavity configuration is shown in figure 4. Aft ramp cavities of three varying angles were used for study. The fore wall of the cavity was modified with a fillet radius of 3mm in order to study the characteristics of the flow. Cavities used for this study were detailed in Table 2.

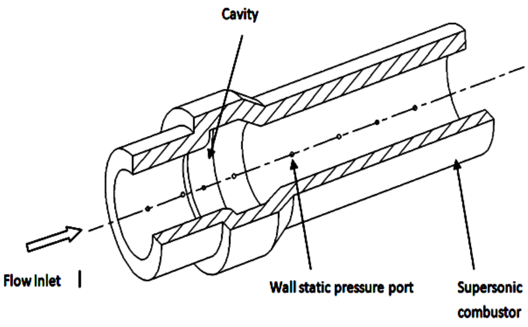


Figure 3 Supersonic test Facility

Wall static pressure taps of 1.0 mm in diameter were placed along the combustor wall in the stream direction to observe the wall static pressure distribution. The wall pressure was measured by scanning type pressure sensors. Static and stagnation pressures were measured at the exit of the combustor using long cone static probe and pitot total pressure probe in order to examine the characteristics influenced by the cavities. A traversing mechanism was used to move the probes in radial direction of the flow field.

Parameter	Nozzle
Stagnation. Pr.	0.3 MPa
Total Temperature	300K
Mach No.	1.3
Mass Flow Rate	0.2 Kg/s

Table 1 Inflow Conditions of Combustor

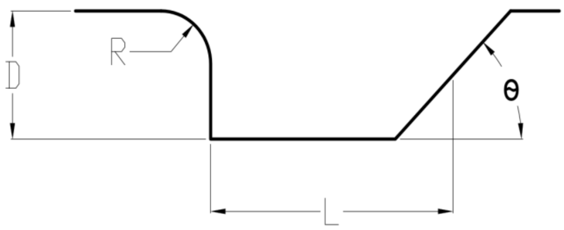


Figure 4 Cavity Layout

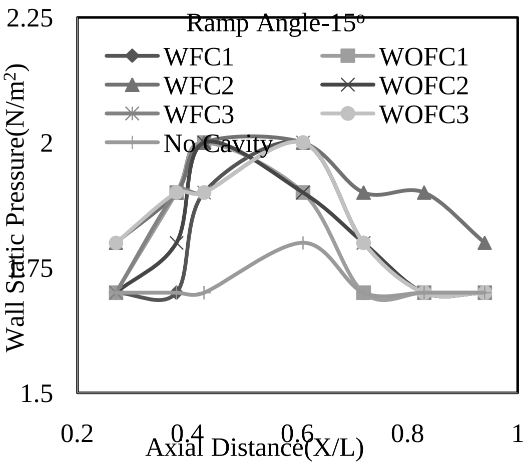
Table 2 Details of cavity configurations

Cavity Confg.	Length (mm)	Depth (mm)	L/D (mm)	Angle ° (degree)
1.	15	3	5	15,20,30
2.	15	4	3.4	15,20,30
3.	15	5	3	15,20,30

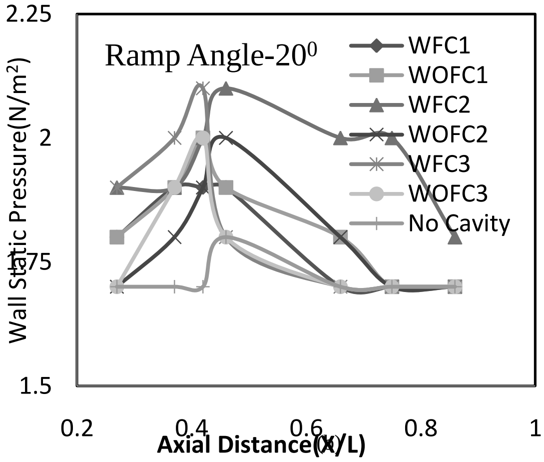
III. RESULT AND DISCUSSION

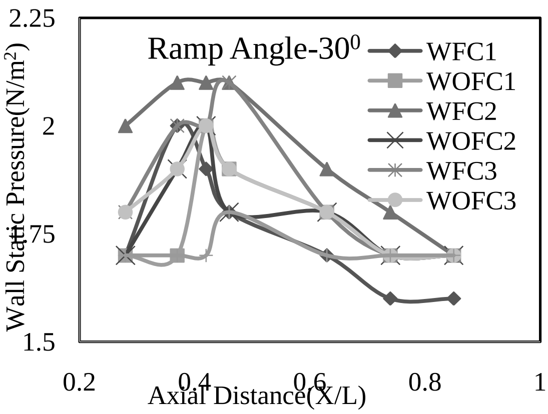
Centre line wall static pressure with various aft ramp cavities were plotted against non-dimensional combustor length X/L, as shown in figure 5. X is measured from the combustor inlet for no cavity for which the wall static pressure seems almost to be uniform along the length of the combustor thereby showing the result of poor mixing.

From the figure 5 it is observed that the wall static pressure rises in the cavity region showing enhancement in active participation in the cavity region alone. By introducing aft ramp cavity with fore wall fillet modification, it shows a significant improvement in the upstream and cavity region of the flow. This is due to the fact that the shear layer which separates from the leading edge of the fore e wall fillet cavity moves in the upstream direction of flow whereas with absence of fillet cavities the shear layer separation occurs at the leading edge of the cavity. It is also observed that increasing the cavity depth also enhances the cavity recirculation and thereby increasing the wall static pressure distribution over the entire region of the combustor. From the above plot for the cavity configuration-II of L/D=3.4 shows higher uniform wall static pressure distribution over the entire combustor.



(a)





(c)

Figure 5 Wall Static pressure distribution for various cavity ramp angle

Figure 6 shows the wall static pressure root mean square (rms) for cavity configuration 2 for various ramp angles between 15^0-30^0. From the plot it is observed that by increasing the ramp angle, the wall static pressure rms value increases for the same combustor. Similar conclusions were made by Mohamed ali and kurian[19]. It is also revealed that fillet cavities shows higher values than that of the absence of fillet cavities thereby showing superiority of mixing over other cavity configurations.

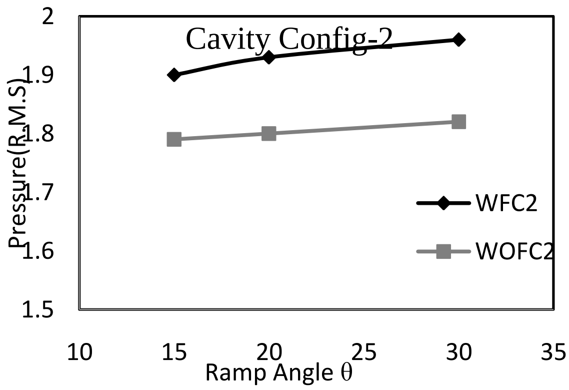


Figure 6 Wall pressure rms for various ramp angles of cavity configuration -2

Stagnation Pressure loss:

It is necessary to analyse the stagnation pressure loss associated with the cavity flow due to the enhancement in mixing. The difference in total pressures at the inlet of the combustor and at the outlet of the combustor to the inlet of the combustor is calculated as the stagnation pressure loss.

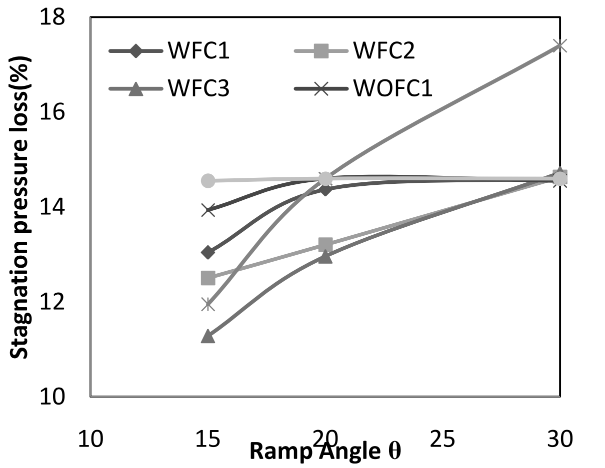


Figure 7 Stagnation Pressure loss for various cavity configuration

Figure 7. shows the stagnation pressure loss associated with various cavity configurations. For the same cavity configuration with fillet at the fore wall of the cavity shows less stagnation pressure loss than that of without fillet cavity.

From the above observation it is evident that cavity configuration-2 with fore wall fillet modification shows better mixing and flame holding characteristics with optimum stagnation pressure loss than any other cavity types.

IV. CONCLUSIONS

Experiments on aft ramp cavities with and without fore wall filet modifications were investigated in a blow down type supersonic flow facility. The facility provides a flow Mach number of 1.3 with a total pressure of 0.3MPa at a total temperature of 300K. The wall static pressure measurement reveals that the cavity with increased aft ramp angles enhances the pressure rise in the upstream of the flow irrespective of cavity with or without fillet configurations. The pressure rms results reveal the superiority of mixing in fillet cavities when compared with the cavities without fillet.

ACKNOWLEDGEMENT

This work is supported by the Department of Science and Technology India under Grant no: SR/FTP/ETA-55.

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