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Technical Notes

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Cavity–Based Injections into Supersonic Flow

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Introduction

RAPID mixing between fuel and air during the short residence time with acceptable total pressure loss is essential for a robust fuel-injection system in a scramjet combustor. At the same time to stabilize combustion, the fuel-air mixture within the flame-holding region must be appropriate and controllable over a wide range of operating conditions. Recently attention has been focused on the use of wall-mounted cavities to assist mixing as well as for flame holding as a result of large recovery of total temperature of the freestream within the cavity. It is found that the acoustic oscillations imposed by flow past open cavities are strong enough to enhance mixing.[1,2] The recirculation region created inside the cavity with hot pool of radicals can ignite and sustain stable combustion by reducing the ignition delay time.[3,4] Basically the factors important for development of suitable cavity configuration for a dual-mode scramjet combustor are the ratio of its length L to depth D, entrainment rate (depends on L), residence time (measured by D), cavity drag, and the static pressure inside the cavity.[5,6] Many researchers suggested that cavities with aft wall ramp could give a good result compared to simple rectangular cavities for flame stabilization.[3,4,7] But the passive stabilization performance of combustion at a different operating condition might actually be worse than that without passive control.[8] Studies on combustion stabilization using liquid kerosene as the fuel showed that combined open and closed cavities demonstrate better combustion performance than single cavity.[9] Moreover it is understood that the injection scheme and location will have a severe effect on the sustained combustion. So the key issue facing the design of an optimum flame-holding system is the ability to synchronize with the changing characteristics of the flowfield depending on the operating mode of the combustor. A robust flame holder must tolerate the flowfield changes without loss of effectiveness.

An active method of mixing enhancement and combustion control is introduced by suggesting the fuel injection into the core of the main flow from the base of a shallow open cavity at different floor locations. The proposal is to control the entrainment of mainstream air into the cavity by the injectant fuel jet, rather than by changing the cavity geometry, so that changing the injection pressure can further control the entrainment rate. On the other hand, growth rate of the fuel jet plume increases considerably as it interacts with the cavity-influenced flowfield. Flame-holding capability of the cavity can be improved by direct cavity fueling from appropriate injection location so as to give uniform fuel distribution with a stable flowfield. The present work focuses on the fundamental studies of the cavity flowfield by employing different injection pressures and locations using sonic air jets. The mean surface pressure and unsteady pressure measurements along with schlieren photography are the diagnostic methods used in this investigation.

Experimental Procedure

The experiments are performed in the Gas Dynamics Laboratory, Indian Institute of Technology Madras. The blowdown supersonic test facility consists of a two-dimensional convergent-divergent (C-D) nozzle designed for a Mach number of 1.76 ± 0.02 exiting in to the test section. The stagnation pressure of the nozzle is 5.3 bar (absolute) at 305 K, and the corresponding airflow rate is $\sim$1.4 kg/s. The constant-area test section is of 56 mm width, 30 mm height, and 300 mm long and has a removable cavity block with cavity length $L = 90$ mm and depth $D = 15$ mm. Air is used as the injectant, too. The injection ports are single row, arranged along the centerline in the cavity floor, that is, T1, T2, and T3 at nondimensional distances, $X/L = 0.22$, 0.44, and 0.66, respectively, and also in the cavity walls A1 and A2 for axial injection as shown in Fig. 1.

The injectant flow rate for the maximum jet pressure condition in the experiment 7.7 bar (abs) is $\sim$0.02 kg/s. A piezoelectric pressure transducer (PCB, Piezotronics, USA, Model 112A22) is flush mounted with the cavity floor at $X/L = 0.78$ P for unsteady pressure measurements. The sensitivity of the transducer is 100 mV/psi, and its natural frequency is 250 kHz. The sampling frequency employed is 10 kHz based on the estimated frequency of the cavity tones. The scan time for each of the samples is 10 μs, which is five times the rise time of the transducer. Fast Fourier transform is performed on the voltage output signals in order to give frequency of unsteady pressure oscillations. Root-mean-square value of the pressure fluctuations is found and is normalized with the freestream dynamic pressure to reduce in to coefficient form $Cprms$. Pressure ports are arranged uniformly 10 mm apart along the cavity floor for mean surface-pressure measurements. The measured values are also reduced to coefficient form Cp and are presented in graphs for comparison. A pressure scanner (Scanivalve Corporation, USA, Model SDIU MK1) is used to scan the mean static pressure. The response time of the transducer is 0.1 ms, and its sensitivity is 75 mV/psi. The

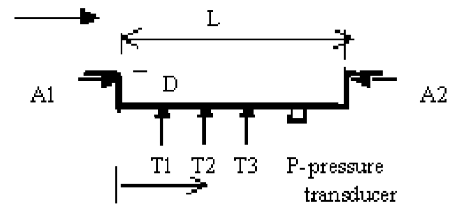

Fig. 1 Details of cavity configuration showing different injection locations.

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specified accuracy of the transducer is ±0.1%, and the uncertainty of the experimental data is estimated to be 0.32% for the pressure coefficient values. The time-averaged schlieren photography is used in this investigation in order to visualize the flowfield with and without injection. The knife edge is oriented vertically to capture the density gradients in the flow direction

Results and Discussion

The pressure distribution inside the cavity is experimentally studied after injecting the air at sonic condition for the maximum jet pressure condition from the three floor locations. The results are compared with the no-injection case as shown in Fig. 2. It is seen that for all of the injection the cavity pressure level is higher than that of the no-injection case, indicating the entrainment of additional air as the injectant jet encounters the freestream in the vicinity of the cavity. The pressure level inside the cavity for T2 injection, located further down stream, is comparatively higher than T1 injection case as expected because of the increase in room for fluid entrainment. This observation is consistent with the increased flow expansion downstream of the leading-edge compression wave as visualized by the schlieren photography (Fig. 3c). Also the pressure rise near the injection location (Fig. 2), showing the deceleration of the entrained air, can be as a result of the flow obstruction by the airjet. In the case of T3 injection that is located away from the leading edge, the jet penetration is considerably affected compared to the other two cases as visualized from the schlieren photography (Fig. 3d). This might be caused by the acceleration of the freestream away from the compression wave. The decrease in cavity pressure level observed for this case should be as a consequence of aforementioned decrease in jet penetration. One important observation is that the active entrainment control obtained here is without affecting the cavity geometry. The flow recompression towards the rear end of the cavity is not altered considerably compared to the no-injection case as seen from the plot. Here it is justifiable to believe that the

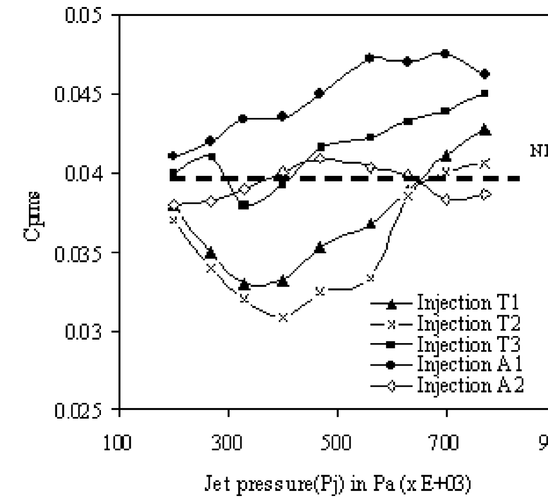


Fig. 4 Unsteady pressure fluctuations at $X/L = 0.78$ on the bottom of the cavity (NI, no-injection case).

cavity drag, which is one of the key design parameters, is not much affected because of additional fluid entrainment. Cavity pressure measured at varying jet pressure conditions indicates that changing the jet pressure depending on the operating conditions could control the cavity entrainment. The schlieren pictures give qualitative information on the injectant jet growth and its penetration into the mainstream. These aspects together with certain interaction with the leading-edge compression wave and its reflection can be thought to be positively contributing to the jet mixing. Mixing effectiveness is found to decrease as the injection location is away from the leading edge as shown in Fig. 3d. This may be considered as a direct consequence of the afore mentioned mainstream flow acceleration.

Root-mean-square pressure fluctuations $Cprms$ are measured at P corresponding to different jet pressure conditions for the two axial-injection cases in addition to the floor injections and are compared with the no-injection case as shown in Fig. 4. The magnitude of $Cprms$ obtained for the no-injection case here is 0.04, and the value found is in reasonable agreement with that reported from similar flow conditions.[10,11] As observed from the plot, the low jet pressure conditions of floor injections, as a means for cavity fueling, seem to damp the cavity oscillation to some extent,[12] especially for T1 and T2 injections. On the other hand, the effect of mainstream fluid entrainment as a consequence of high jet pressure conditions on the pressure fluctuations are insignificant compared to the no-injection case. But for T3 injection, which is located near the trailing edge, where the cavity vortex is expected to be stationed, cavity fueling might reinforce the vortex initially and enhance the pressure oscillations. As the jet pressure increases, it could interact with the sensitive end of the shear layer and can excite the pressure fluctuations. In the case of axial injection (location A1), it is seen that the cavity fueling from the front wall in the direction of flow considerably enhances the cavity pressure fluctuations, and its intensity also is found to increase with jet pressure. This might be because the jet assists the shear-layer oscillations as it moves in the direction of flow[13] and consequently reinforces the cavity vortex located near the trailing edge. But in the case of the aft wall injection (location A2), the cavity oscillations are suppressed by the jet flow compared to front wall injection, and improved uniformity of cavity fueling could be expected because of increased residence time. This is corroborated by the previous findings.[8] However, these observations do not throw light on the available fuel-air ratio in the flame-holding region as a result of the cavity-based injection.

The oscillation frequencies are also presented in addition to the magnitude of pressure fluctuations to see the response of the cavity with jet pressure and injection locations as shown in Fig. 5. The frequency values are compared with those of the no-injection case as well as semi-empirical model.[10] The frequency of dominant pressure oscillation obtained for the no-injection case here is 2740 Hz and corresponds to the second harmonic. But there is no mode shifting

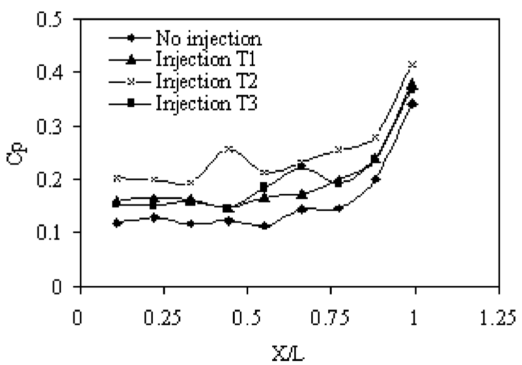
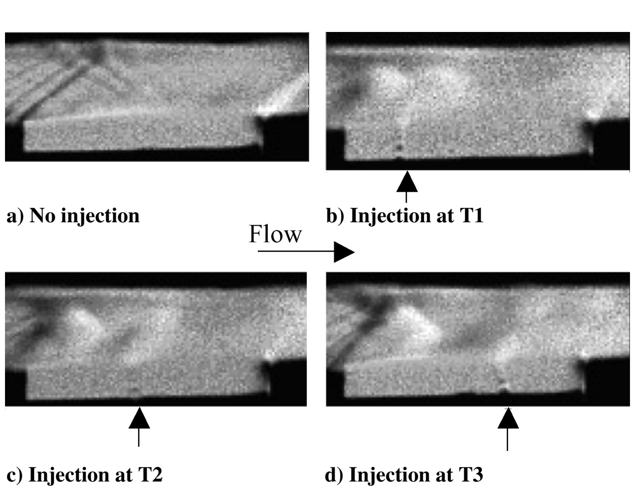


Fig. 2 Cavity floor pressure distributions *Cp*.



a) No injection **b) Injection at T1**

c) Injection at T2 **d) Injection at T3**

Fig. 3 Schlieren photography of the cavity flowfield.

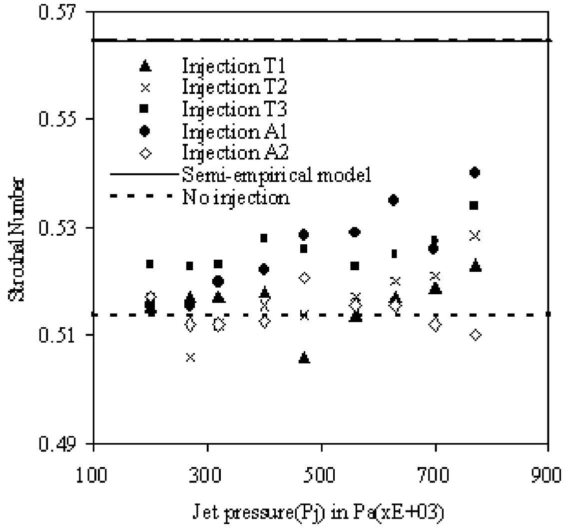


Fig. 5 Variation of oscillation frequency (Strouhal number) with jet pressure and injection locations.

observed irrespective of the injection conditions. Even then there are changes in the frequency values depending on the injection location and jet pressure. Moreover the frequency response of the cavity observed is not uniform, which might be because of the complex nature of the cavity-jet interaction flowfield. As observed from Fig. 5, only T3 injection shows a significant increase in the oscillations frequencies from that of the no injection in the low jet pressure range. In case of the higher jet pressure conditions, all of the injection locations show comparatively higher oscillation frequencies except A2 injection. These observations give an indication about the optimum injection locations and jet pressure control for effective fueling with a stable flowfield, depending on the operating conditions.

Conclusions

Injection behind the leading-edge compression wave of a shallow open cavity is demonstrated here to mix air with fuel and for active flame stabilization. This technique however reduces the pressure loss, enhances mixing, and increases the cavity entrainment rate as well as the fluid residence time in the flame-holding region. Cavity fueling from a suitable location can suppress the cavity oscillations to some extent and can improve the fuel distribution. A detailed study of the jet-cavity flow interaction characteristics in this respect can explore more details and is useful for optimizing the injection scheme and locations.

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