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Flow-acoustic Characterisation of a Cavity-based Combustor Configuration

Krishna Kant Agarwal* and R.V. Ravikrishna
Indian Institute of Science, Bengaluru–560 012, India
**E-mail: krishnak@mecheng.iisc.ernet.in*

ABSTRACT

This study concerns the flow-acoustic characterisation of a cavity-based combustor configuration. A well-validated numerical tool has been used to simulate the unsteady, two-dimensional reacting flow. Initially, a conventional flow over a cavity with dimensions and conditions corresponding to a compact cavity combustor was studied. Cavity mass injections in the form of fuel and air injections required for trapped vortex formation were then employed and the resonance features of this configuration were studied. The results indicate that the cavity depth mode resonance mechanism is dominant at the conditions studied in this work and that the oscillation frequencies do not change with cavity air injection. This observation is important since it implies that the only important variable which can alter resonant frequencies is the cavity depth. With combustion, the pressure oscillation amplitude was observed to increases significantly due to periodic entrainment of the cavity air jet and fluctuation of fuel-air mixture composition to produce highly fluctuating heat-release rates. The underlying mechanisms of the unsteady flow in the cavity combustor identified in this study indicate the strong dependence of the acoustics on the cavity injection strategies.

Keywords: Flow-acoustics, cavity combustor, turbulent reacting flow, unsteady flow, cavity fluid mechanics

NOMENCLATURE

Ma	Mach number
L	Cavity length
D	Cavity depth
k	Turbulent kinetic energy
ϵ	Turbulence dissipation rate
f	Frequency
c	Speed of sound
U	Free-stream velocity
*f*D/c*	Cavity-reduced frequency (Helmholtz number)
*f*L/U*	Strouhal number

1. INTRODUCTION

A new cavity-based combustor concept has been studied for its multiple advantages. The flow field in the combustor is different from that of the classic flow over a cavity problem, owing to the injection of fuel and air into the cavity. Flow-induced acoustic resonances inherent in the classic problem of flow over a cavity are well reported[1-4]. These resonances can occur through various mechanisms depending on free stream Mach number and cavity length-by-depth ratio. In low-velocity subsonic flows ($Ma < \sim 0.3$), acoustic resonance similar to that in a Helmholtz resonator is known to occur for deep cavities ($L/D <\sim 1$)[5]. The resonant frequency in this mode is primarily dependent on cavity dimensions, namely depth and length-to-depth ratio (*L/D)* and broadly independent of flow velocity[4-6].

For shallower cavities ($L/D > 1$) at higher subsonic velocities, organized shear layer oscillations and corresponding acoustic resonances are predominant[3]. While the original work on shallow cavity resonance dates back to Rossiter[1], a considerable interest has revived in the recent decade. Recent studies concentrate on increasing the basic understanding of cavity fluid mechanics to help in improved design of acoustic actuators to control cavity resonant behaviour[3, 7-9]. In the shallow cavity shear layer mode, cavity resonant frequencies are dependent mainly on cavity length and free-stream velocity, and are well-predicted by a semi-empirical Rossiter formula[1].

The present cavity-based combustor concept offers excellent combustor operation reliability due to flame stabilisation in a physical cavity and consequently, the capability of ultra-lean operation[10]. Additional benefits are low pressure drop due to absence of swirl and low NO_x due to segregated richness combustion zones. Fluid dynamical studies on this concept[10,11] have concentrated mainly on achieving a steady-flow field for flame stabilisation and minimisation of pressure drop, but a discussion on fluid-acoustic characteristics of this combustor is not present in the literature available. The objective of the present study is to fill this gap in the literature. Pressure fluctuations and flow oscillations in compact combustors may lead to disruption of steady reactant flow patterns and ultimately to large-scale flame oscillations, which can eventually cause flame blow-out. Therefore, characterisation of flow-acoustic phenomenon in this combustor design is important not only from noise considerations and preventing material fatigue, but also important from the flame stabilisation standpoint.

Figure 1 shows the schematic of flow configuration currently being studied. This schematic corresponds to an experimental rig designed to study a sector of a possible design for an annular gas turbine, albeit in a two-dimensional manner[12,13]. The length-to-width (L/W) ratio of this rig has been

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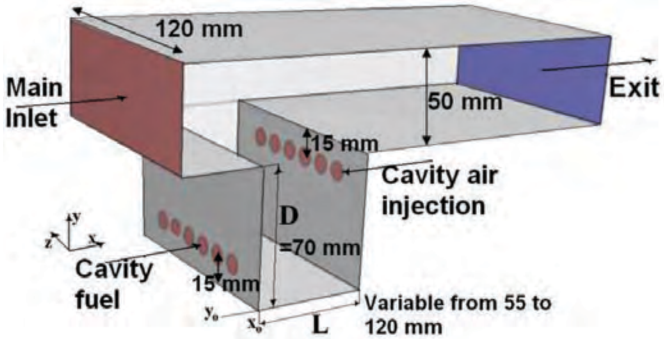

Figure 1. Flow configuration and schematic of the cavity-based combustor.

selected based on detailed studies to ensure that the flow is two-dimensional is nature[12,13]. Hence, all simulations presented in this paper are two-dimensional. At one side of this duct, a rectangular cavity is formed wherein fuel is injected deep inside. Air is injected into the cavity from the wall opposing the mainstream to produce high levels of shear as suggested[14]. Flame stabilisation requires the L/D to remain between 0.5 and 1.2. Typical cavity L/Ds employed in the present configuration are close to unity where both acoustic resonance and Rossiter's shear layer theories overlap. Mach numbers in gas turbine combustors also lie in the intermediate subsonic range which again restricts the direct application of any well established resonance theory for this configuration. Since the acoustics of the current configuration lie in the overlap region of the two resonance theories, there is a need for detailed studies on the unsteady flow-field structure. The approach adopted in this study is to use a validated numerical tool to study flow-acoustic resonance phenomenon in the above-mentioned configuration. The first step was to identify the predominant flow-acoustic resonance mechanism in the combustor geometry being studied, without any cavity injection and with only mainstream flow. The next step was to find if there is any alteration in the oscillation mechanism with cavity mass injection which is required for the trapped vortex flame stabilisation. Finally, the complete problem with cavity mass injection and combustion was studied to investigate the individual contribution of each of these factors to the flow-acoustic resonance of the combustor.

2. NUMERICAL MODEL AND VALIDATION

KIVA-3V[15], a numerical tool for unsteady reacting flow simulations was adapted for this study. Unsteady Reynolds-averaged Navier-Stokes equations were solved with the k-ϵ turbulence model and a modified eddy dissipation concept[16] for simulating combustion. The details of the numerical code can be found in the KIVA-3V manual[15]. For simulations, a two-dimensional computational mesh was employed with periodic boundary conditions in the third direction. All inlets were specified with velocity boundary conditions and outlet with constant pressure non-reflecting boundaries. Inlet temperature of 300 K and pressure of 1 atm were specified. A grid-independence study was carried out for 2-D configuration of the combustor and a computational mesh with 4000 cells and minimum resolution of 0.8 mm at cavity leading edge was able to capture major features of the shear layer dynamics. The grid-independence results in terms of invariance of 1st fundamental frequency are shown in Table 1.

Table 1. Grid independence for capturing cold flow oscillations frequency in the cavity-based combustor.

No. of cells in computational domain (2-D)	Fundamental frequency of pressure oscillations (Hz)
1700	220
3276	280
4036	287
5058	288
13456	288

For validation of the numerical tool, experimental data was taken from the studies of Cattafesta[17], *et al*. These experiments have been carried on a cavity of length 6 inches attached to wind tunnel of cross-section 6" x 2". Experimental conditions of the following two cases were taken for validation comparisons:

Case 1. Free stream Mach No. = 0.4, L/D = 2, $Re_{(L)}$ = 2.5 e^{+6}.
Case 2. Free stream Mach No. = 0.6, L/D = 4, $Re_{(L)}$ = 3.0 e^{+6}.

Pressure data from simulations was taken at the experimental probe location and analysed using a 512-point FFT. The sampling time step was 1.5 x 10^{-4} s, which gave spectral resolution of 13 Hz and Nyquist frequency of 3333 Hz. The aliasing effect and sampling invariance were checked by employing twice and thrice sampling rates. However, peaks beyond 3300 Hz were associated with negligible power. Figure 2 shows the pressure oscillation spectrum obtained in the numerical simulations of Case 1. A comparison of frequency peaks pressure spectrum in simulations with experiments is shown in Table 2. It was observed that frequencies were captured well within the spectral resolution. The excellent agreement with experimental frequency values and facility of multiple computationally affordable simulations enable utilisation of the numerical tool for exploring resonant mechanism in the configuration studied.

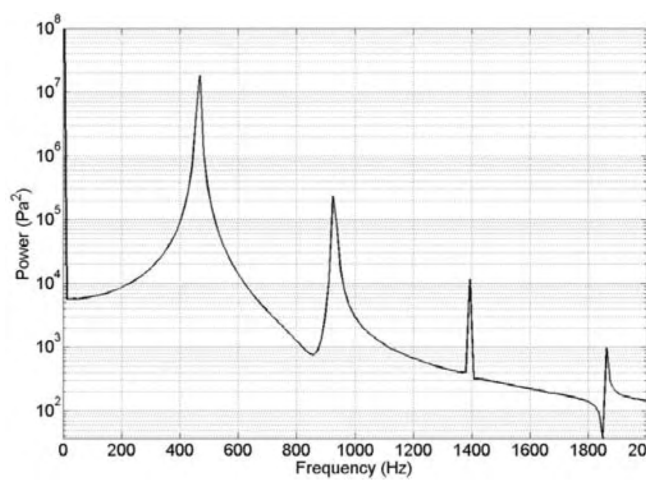

Figure 2. Predicted pressure power spectrum for the experimental case of Cattafesta[14], *et al.*

3. FLOW OVER A CAVITY STUDIES

Initially, the plain mainstream flow over a cavity with

Table 2. Resonant frequency comparison of predictions with experiments of Cattafesta[17], *et al.*

Case	Mode (Order of the resonant peaks)	Experiments of Cattafesta[17], *et al.* (Hz)	2-D KIVA-3V simulations (Hz)
1	I	475	480
1	II	860	865
1	III	1355	1390
2	I	510	508
2	II	1135	1020
2	III	1760	1590

L/D = 1 was studied. It was found in the grid-independence study that the fundamental resonant frequencies become grid -independent once the 2-D computational domain is resolved with a mesh having 4000 faces and minimum resolution of 0.8 mm at cavity leading edge. This computational mesh is shown in Fig. 3. This mesh is also able to capture essential features of the shear layer dynamics, as shown in Fig. 4. The shear layer oscillation features captured in Fig. 4 show regular rolling up of vortices near the leading cavity edges where the incoming boundary layer separates from the wall. Acoustic waves in the cavity cause periodic fluctuations of boundary layer thickness and result in discrete vortices[6, 18]. As mentioned earlier, the cavity L/D and Mach number selected do not clearly fall in the range covered by the two cavity resonance theories, and thus, actual resonant behaviour was investigated here. To accomplish this task of identifying the dominant resonant mechanism, a

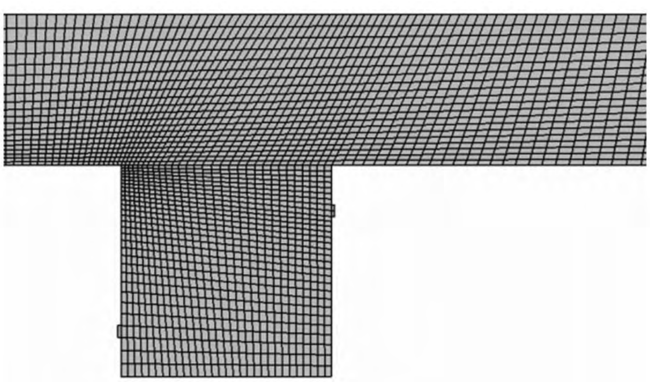

Figure 3. Computational grid used for the two-dimensional simulations of the cavity-based combustor.

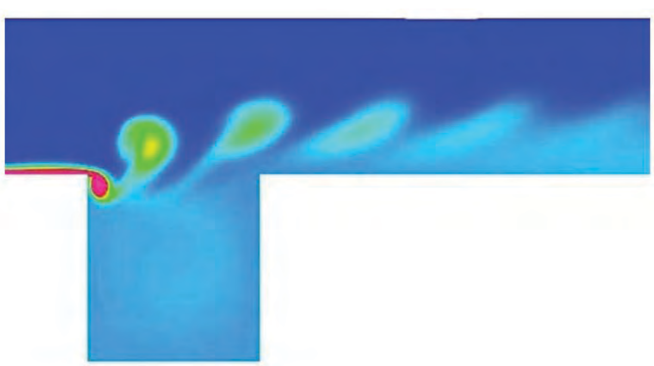

Figure 4. Structure of shear layer oscillations for the plain flow in the cavity-based combustor, visualised by injecting trace species at the base of the inlet.

range of conditions was studied at mainstream velocity ranging from 10 m/s to 150 m/s. Results show that the frequency variation with flow velocity does not follow the dependence as predicted in the Rossiter's model and acoustic oscillations are in better agreement with linear cavity depth resonator model. The results are the same as those presented in Fig. 6 with cavity injection, and therefore, additional figure is not presented. The absolute values of *f*D/c* satisfying the simulations were 0.08, 0.2, 0.37, 0.54 and 0.61. The available literature shows a spread in absolute values of the cavity-reduced frequencies which are derived from a curve fit to the actual results[4, 6]. At higher Mach numbers, the shear layer oscillations are known to be dominant and it was also observed that *f*D/c* lines asymptote to Rossiter lines in the results of the present simulations.

To confirm the presence of the depth mode resonance mechanism, simulations were performed at varying cavity depths and L/Ds. While Rossiter modes are linearly dependent on cavity length and independent of cavity depth (negligible variation with L/D = 1 to 4)[3], depth modes are independent of length and linearly dependent on the cavity depth. Figure 5 summarises results from these simulations showing linear variation of resonant frequency peaks with cavity depth. For a constant cavity depth, L/D variation implies a change in cavity length, but there is no appreciable change in resonant frequency values with L/D variation. Therefore, it can be concluded that resonant frequencies in this cavity-based combustor configuration are independent of cavity length as well as also flow velocity as is shown in Fig. 6. It can be concluded that Rossiter modes may not have any significance for cavity resonance in the present configuration. This insight is helpful from the design point of view, as the cavity dimensions can be selected based only on the depth to avoid resonance with turbine and compressor oscillations. Additionally, it can be ensured that for the dimensions selected, the possibility of further resonances with changing flow conditions is absent.

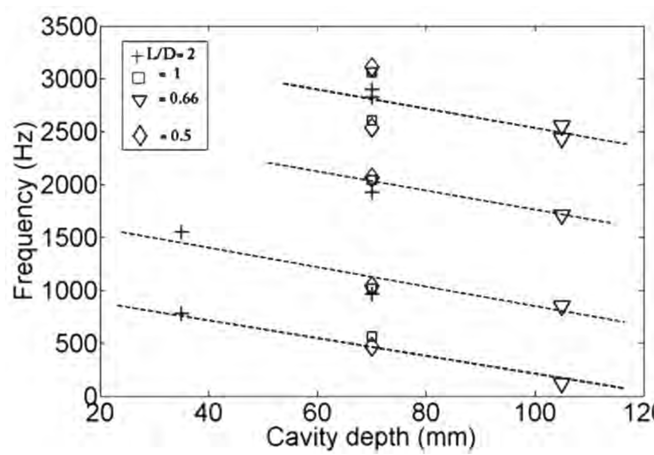

Figure 5. Variation of pressure oscillation frequencies with cavity depth and L/D **at constant mainstream velocity of 100 m/s.**

4. CAVITY INJECTION STUDIES

Injection of fuel and air into the cavity is required in the combustor for flame stabilisation and enhancing the cavity vortex strength. It is observed from Fig. 6 that with cavity mass injection also, the resonances in the present configuration

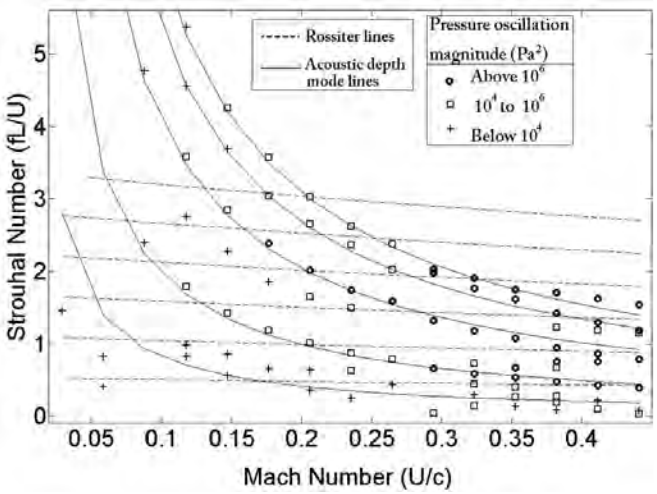

Figure 6. Peak frequencies in pressure oscillation spectra at increasing mainstream velocity with constant cavity injection. (Cavity air velocity = 50 m/s, cavity fuel = 10 m/s). Strouhal number (*f*L/U*) vs Mach number is shown with Rossiter and cavity depth mode lines for comparison. Dependence on depth modes is observed.

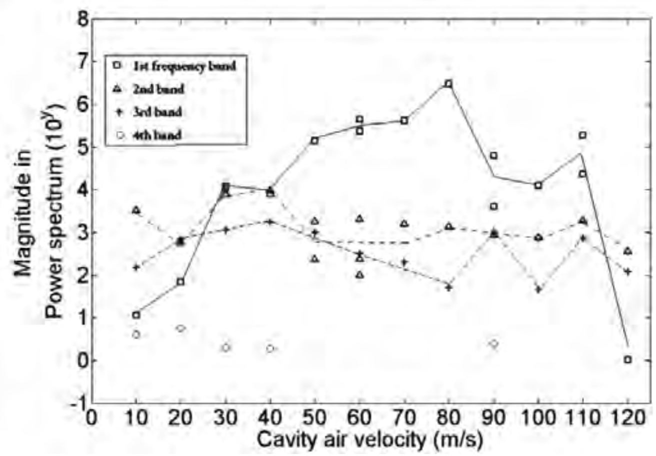

Figure 7. Variation of acoustic power in the four frequency bands with cavity air injection (Mainstream velocity = 30 m/s).

are primarily associated with the cavity depth modes. While cavity fuel injection velocity is very small compared to the mainstream, the cavity air flow rate is sufficiently large to alter flow characteristics. Therefore, at a constant mainstream velocity of 30 m/s and nominal fuel velocity of 10 m/s, the effect of cavity air injection was assessed by increasing its value from 10 m/s to 120 m/s in steps. On comparison with the frequency peaks for the plain mainstream flow case, it was observed that there was no appreciable change in the value of resonant frequency peaks with cavity injection. The primary reason for this behaviour is the association of the resonance only with the cavity depth. In Rossiter's shear layer oscillation mechanism, frequencies would have substantially changed with cavity air injection due to change in shear layer dynamics. But the lack of dependence of these frequencies on flow conditions confirms the cavity depth mode resonance, as the geometry-dependent acoustic resonances are quite insensitive to the actual nature of the forcing perturbations. However, there is a clear variation of acoustic power contained in the various frequency bands as shown in Fig. 7. In general, the acoustic power in the fundamental mode is observed to rise gradually with cavity air velocity and then decrease or increase abruptly. The flow is quite complex with cavity injection and it is not clear how this mode switching occurs. In general with the cavity injection, acoustic power is observed to be higher for the same frequencies as compared to that in the plain mainstream flow. This variation in the acoustic power level may be arising from the complex mainstream and cavity air interaction, on which further studies are required. However, it is speculated that the cavity air injection increases dynamic energy in the shear layer due to which there may be occurrence of feed-forward amplification.

Figure 8 shows the nature of flow oscillations with cavity mass injection, visualised by colouring the boundary layer with a tracer. A flapping movement of the mainstream flow into and out of the cavity was observed which indicates the dominance of pressure oscillations along the cavity depth. The fuel distribution patterns can get substantially affected with these flow oscillations which can result in further spatio-temporal variations of local equivalence ratios in the combustor. This is expected to result in large variations in temporal heat releases which will further affect the pressure rise and acoustic radiation.

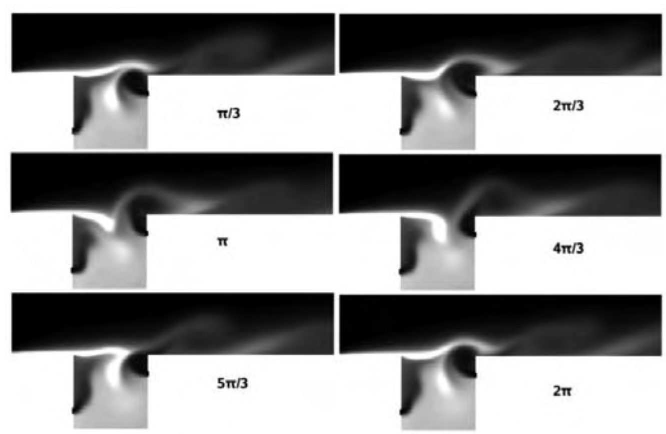

Figure 8. Instantaneous images of a trace species injected at the base of the inlet to visualise the shear layer. (Mainstream velocity = 30 /s, cavity air = 50 m/s, cavity fuel = 10 m/s). The phase angle corresponding to each image is also indicated.

5. PRESSURE SPECTRUM WITH COMBUSTION

While there is large body of literature available on the principles of acoustic wave interaction with combustion in premixed flame systems[19], studies on systems with non-premixed reactants are scarce as pointed out by Tyagi[20]. Schadow and Gutmark[21] summarise a few key features of the combustion instabilities occurring in non-premixed combustion systems. Vortex shedding in a bluff-body stabilised flame can cause spatio-temporal variations in fuel distribution in the flow field. The rolling up of vortices can entrain significant amount of reactants which are not mixed at molecular levels. Impingement of these vortices and subsequent breakup can lead to vigorous small-scale mixing, leading to rapid combustion and heat release. Periodic pressure variations associated with these heat release bursts can act as an acoustic source which can amplify the oscillations to undesirably high magnitudes in many configurations. However, the exact nature of this mechanism is highly dependent on reactant injection strategies, bluff-body configuration and positioning. Hence, numerical modelling of the combustion is also performed for this configuration to study the acoustic characteristics. The modelling approach and the details of the combustion model can be found elsewhere[14].

Figure 9 shows a comparison of the pressure-time trace at the cavity top, in reacting and non-reacting flows at identical flow conditions. It was observed that the pressure oscillation magnitude was increased with combustion, as compared to that in the cold flow case. As revealed from the temperature contours shown in Fig. 11, reacting flow oscillations had spread to a larger extent both in and out of the cavity as compared to the cold flow case (Fig. 8). The cavity air jet gets periodically entrained in the cavity causing the reacting mixture to attain near-stoichiometric values, by fresh supply of the oxidiser to the fuel in the cavity. This results in rapid combustion and higher heat release, and consequently, a higher pressure rise. With high pressure in the cavity, the cavity products are pushed out and the cavity air jet gets deflected out of the cavity. This results into the scarcity of air or oxidiser, and consequently, the heat-release rate reduces. Thus, the low pressure portion of the acoustic wave encounters a pressure reduction due to escaping cavity products and lower heat release. This overall phenomenon results in large amplification of the acoustic waves with combustion as shown in Fig. 9. As observed from the comparison of the acoustic spectra in Fig. 10, the pressure oscillations exhibit a higher acoustic power with combustion as compared to the cold flow, and a complex broadband behaviour occurs instead of well-defined peaks. Such high acoustic amplification with combustion has implications both for the noise level during combustor operation for flame stability. Additional studies are required to focus on flame stabilisation with damping of these flow oscillations. However, this work has provided sufficient guidance on underlying physics of the cavity-based combustor acoustics and primary reasons for the acoustic amplification with combustion. Therefore, attempting further design changes such as flow stabilisers or exploration of appropriate injection strategies, can form the basis for future studies.

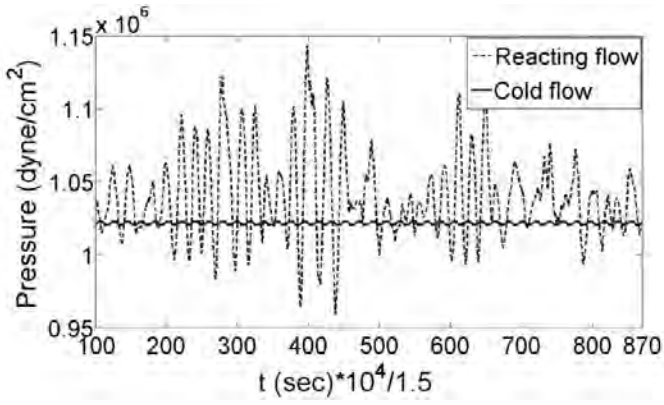

Figure 9. Comparison of reacting and non-reacting flow oscillations, main air velocity = 30 m/s, cavity air velocity = 100 m/s, cavity fuel velocity = 10 m/s.

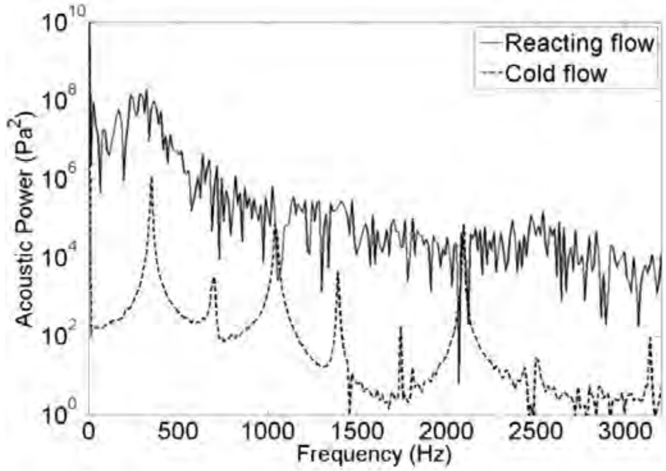

Figure 10. Spectrum comparison of reacting and non-reacting flow oscillations, conditions same as in Fig. 9.

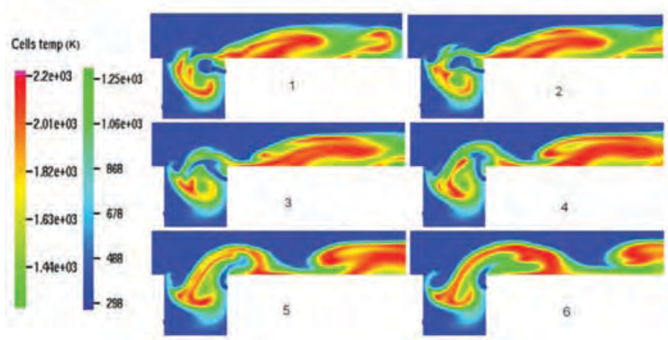

Figure 11. Instantaneous temperature contours for the two-dimensional unsteady reacting flow field simulations, the flow conditions are same as those in Fig. 7. The individual figures are instantaneous in equispaced succession over a period of 5 ms.

6. CONCLUSIONS

This study concerns the flow-acoustic characterisation of a cavity-based combustor configuration investigated using a well-validated numerical tool. Results indicate that the cavity depth mode resonances are predominant over Rossiter shear layer resonances in the expected combustor-operating range. This implies that resonant frequencies are independent of flow velocity or cavity length, and are dependent only on the cavity depth. The cavity air and fuel injection seem to have no effect on values of resonant frequencies which further confirms the depth-mode resonance. Acoustic power increases with cavity injection and also with combustion. Due to the cavity depth mode being the main resonance mechanism, there is a periodic entrainment of cavity air jet in cavity. This causes periodic changes in the cavity fuel-air mixture composition, the heat release and pressure rise, which is finally reflected in the form of substantial amplification of acoustic radiation. Overall, this study highlights the basic underlying oscillation mechanism and the principal factors affecting this mechanism. Exploration of design changes which could lead to damping of oscillations while maintaining good flame stability in this cavity-based combustor configuration would form the basis for future studies.

7. ACKNOWLEDGEMENT

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Contributors

Mr Krishna Kant Agarwal obtained BE(H) (Marine Engineering) from Marine Engineering and Research Institute, Jadavpur University, Kolkata. Currently pursuing his PhD from Combustion and Spray Laboratory, Department of Mechanical Engineering, Indian Institute of Science (IISc), Bengaluru. His area of research includes: Unsteady turbulent combustion simulations using KIVA-3V, experiments on a compact cavity-based combustor concept.

Prof R.V. Ravikrishna obtained his PhD (Mechanical Engineering) from Purdue University, USA. Presently working as an Associate Professor in the Combustion and Spray Laboratory, Department of Mechanical Engineering, IISc, Bengaluru. His area of research includes: Combustion and flow diagnostics using laser-based techniques, spray diagnostics, IC engine in-cylinder processes, alternate fuels, novel combustor development, computational fluid dynamics. He has been awarded with INAE Young Engineer Award in 2004. He has more than 80 research papers in national/international journals and conferences.