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EXPERIMENTAL INVESTIGATION OF ACOUSTIC EXCITATION BY HEAT RELEASE RATE FLUCTUATIONS IN A NON-PREMIXED HALF-DUMP COMBUSTOR

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Abstract

The transition from low-amplitude broadband noise generation to large-amplitude discrete tones due to combustion instability as the flow conditions are gradually varied is experimentally investigated in a half-dump combustor. The length of the combustor duct and the axial location of the step relative the acoustic mode excited in the duct are independently varied. High-amplitude discrete tones are excited under certain conditions when the observed dominant frequency jumps from that of a natural acoustic mode to a vortex shedding mode. This condition is denoted as the onset of combustion instability, and an experimentally determined stability map is obtained of the conditions of the onset of instability. High-speed imaging of the chemiluminescence fluctuations in the flame stabilization zone is performed at different conditions such as far away from onset of instability and after at the onset. Fourier transform of the time variation of the fluctuation in the total chemiluminescent intensity in the combustion zone is performed, and the resulting spectra is correlated with the acoustic spectra observed at the base of the dump plane in the duct. It is observed that the total chemiluminescence spectra show distinct peaks at exactly the same frequencies as the dominant frequencies of the corresponding acoustic spectra, clearly indicating that the heat release fluctuations in the combustion zone are responsible for the excitation of the acoustic oscillations. Further, the different dominant frequencies observed in both spectra can be identified as corresponding to either a vortex shedding mode or an acoustic mode, depending upon the flow conditions relative to the onset of instability, so the results show that the acoustic modes excited in the duct in turn influence the vortex shedding process involved in the heat release fluctuations.

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INTRODUCTION

Combustion instability is a practical problem in engines and power systems involving a complex interplay of unsteady heat release rate in the combustion zone with the acoustic modes of the combustion chamber. One of the important driving mechanisms of combustion instability has been that due to vortex shedding, as highlighted by Schadow and Gutmark [7], who showed that the development of coherent flow structures and their breakdown into fine-scale turbulence can lead to periodic heat release. Many workers have investigated combustor geometries that include a predominant role for vortex shedding, such as dump combustors involving axisymmetric backward-facing step [1,6,8-10] and bluff-body flame-holders [2,3,5]. They have deduced the phase relationship between the vortex roll-up sequence and the heat release fluctuations under conditions of excitation of intense oscillations. Lieuwen [4] has also reported experimental characterization of limit-cycle oscillations in a premixed dump combustor, including examples of transition from stable to unstable combustor operation in the form of supercritical and sub-critical bifurcations.

Almost all the works on combustion instability focus on investigations under conditions when the combustion oscillations are unstable. With a limited exception of Lieuwen [4] recently, there is no systematic work on a wide variation of geometric parameters of the combustor and flow conditions that span from a regime of low-intensity noise generation without appreciable acoustic feedback from the combustion chamber on the combustion process, to a regime of excitation of high-intensity discrete tones symptomatic of combustion instability. The Rayleigh criterion delineates regimes of unstable combustion from those of stable combustion, but it is only a necessary condition, which could be met by a variety and combination of physical mechanisms. These mechanisms would gradually vary in predominance and interplay with each other, leading to a transition from low-amplitude noise to high-amplitude instability conditions. A systematic variation would prompt investigation on the mechanisms that dictate the onset of instability. The data can also serve to identify precursors to instability that can be utilized in actively deploying certain passive control measures in practical combustion systems.

Many past investigators [2,3] have also reported the fluctuations in the chemiluminescent intensity fluctuations in the flame, and have correlated these fluctuations with the acoustic pressure fluctuations to examine the Rayleigh criterion under conditions of excitation of intense oscillations. However, as mentioned above, as the flow conditions transition from those of low-amplitude noise generation to those of intense discrete-tone excitation, the nature of the acoustic spectra changes significantly, and it is important to examine how the corresponding chemiluminescence spectra in the combustion zone varies. Since the chemiluminineescent intensity fluctuations are an indicator of the heat release rate fluctuations in the combustion zone that act as the acoustic heat source, and the heat release rate fluctuations are predominantly influenced by the vortex shedding process, the correlation between the spectra of the acoustic oscillations and the chemiluminescent intensity fluctuations would reveal the interaction between the vortex shedding process and the natural acoustic modes of the combustion chamber as the flow conditions are varied. The past investigators have examined the chemiluminescent intensity fluctuations by means of a photo-multiplier tube interrogating the combustion zone. In the present work, on the contrary, high-speed imaging of the combustion zone is performed, which affords the spatial-temporal resolution of the chemiluminescent intensity variation.

The present paper reports experimental results obtained at this laboratory on a half-dump combustor geometry, which is commonly studied by past investigators. The fuel is injected at the convex corner of the dump plane to co-flow with the inlet air flow, so the configuration is that of a non-premixed combustor. All the previous works have been performed on premixed combustors, so the investigation of non-premixed combustors for combustion instability assumes importance. Acoustic data is obtained over a wide range of combustion conditions from those at which low-amplitude broadband acoustic oscillations are excited to those when intense discrete tones are excited.

EXPERIMENTAL DETAILS

A schematic of the laboratory-scale combustor developed for this investigation is shown in Fig. 1. It is a rectangular geometry of constant width of 60 mm downstream of the settling chamber, to provide access for optical diagnostic investigation later. The settling chamber contracts abruptly into an inlet section with a contraction ratio of 17.45:1, so as to provide a nominally acoustically-open upstream boundary condition. The inlet section consists of flow-straightening tubes and mesh screens to reduce flow non-uniformities, particularly due to the presence of the sudden contraction. The inlet section has a height of 30 mm, and is followed by three sections of the same cross-section until the backward-facing step is reached, namely, an inlet optical-access module and two upstream extension ducts. The test section contains the backward-facing step, whose height has been maintained at 30 mm in the present study. A number of optional downstream extension ducts of different lengths and the same cross-sectional dimensions of the test section (60 mm × 60 mm) are used in combination to vary the overall length of the combustor. Provision is made for injection of fuel through a single port of 4 mm × 4 mm dimension, 1 mm below the top edge of the step along the central plane of the test section. Methane is used as fuel.

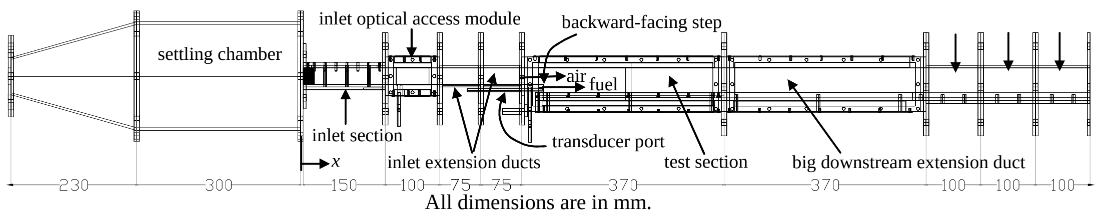


Figure 1 – Schematic of the experimental set-up.

The maximum range of variation of the air flow rate is 350-3550 litres per minute (lpm), in steps of 50 mm; the upper limit depends on the blow-off conditions at a given fuel flow rate. This gives a velocity range of approximately 3-30 m/s and a corresponding Reynolds number range of 3000-60000, based on the step height. The fuel flow rate is varied at the levels of 6, 9, 13, 17, 21, 25, and 29 lpm for each air flow rate, which corresponds to fuel mass flow rate $\dot{m}_f$ in the range of 65-316 mg/s. This spans an equivalence ratio range of 0.02-0.79. The flow rates are measured by conventional rotameters with a measurement error within 2%.

Five wall-mounted acoustic transducer measurements are made simultaneously in each experimental run. The transducers used are of the piezo-electric type, model no. 106B of PCB Piezotronics make, with a sensitivity of 500 mV/psi. The sampling for each of the transducers is done at the rate of 10 kHz to obtain 32768 (2^{15}) samples per channel. Fast Fourier transform (FFT) is performed on the time-series data, with a bin size of 0.3 Hz. The dominant frequencies and their corresponding amplitudes are identified from the Fourier-transformed spectra. Multiple dominant frequencies are identified as local maxima in the spectra. The axial location of the transducer ports are marked as x_P in the figures presenting the results, where x is the axial distance measured from the entry to the inlet section (Fig. 1). One of the transducers is always mounted on the face of the step, at 400 mm from the entry to the inlet section.

High-speed chemiluminescence imaging is performed with a high-speed camera (model HiSiS 2002, KSV Instruments, Finland) at a maximum framing rate of 2250 frames per second. The camera has a pixel resolution of 256 × 256. An optical filter whose spectral transmitivity is centred around 431 nm is used in front of the lens in the camera. The acquired images are digitally processed to obtain the total chemiluminescent intensity fluctuations in the entire field of view to represent the heat release rate fluctuations from a compact combustion zone. Fast Fourier transform of the total chemiluminescent intensity fluctuations is performed to obtain the spectra to compare with the spectra of the acoustic oscillations obtained simultaneously with the high-speed imaging.

RESULTS AND DISCUSSION

Acoustic Measurements

Dominant Frequencies

Dominant frequencies f observed in the spectra recorded at the dump plane are plotted in the form of Helmholtz and Strouhal numbers, defined as $\mathrm{He} = fL/c$ and $\mathrm{St} = fh/U$ respectively, where L is the length of the duct, h is the height of the step, c is the speed of sound at a reference temperature (inlet), and U is the time-mean spatially-averaged velocity at the inlet. A nearly constant value of the Helmholtz number would signify that the observed dominant frequency corresponds to the natural acoustic mode of the duct, although not necessarily with any ideal acoustic boundary conditions. A constant value of the Strouhal number would indicate that the observed dominant frequency corresponds to that due to the vortex shedding process in the flow field, referred to as a vortex shedding mode. Note that when the Helmholtz number is formed based on an observed dominant frequency that corresponds to a vortex shedding mode, it would vary linearly with the air-flow Reynolds number, whereas when the Strouhal number is formed based on a frequency corresponding to a natural acoustic mode of the duct, it would vary hyperbolically with the air-flow Reynolds number.

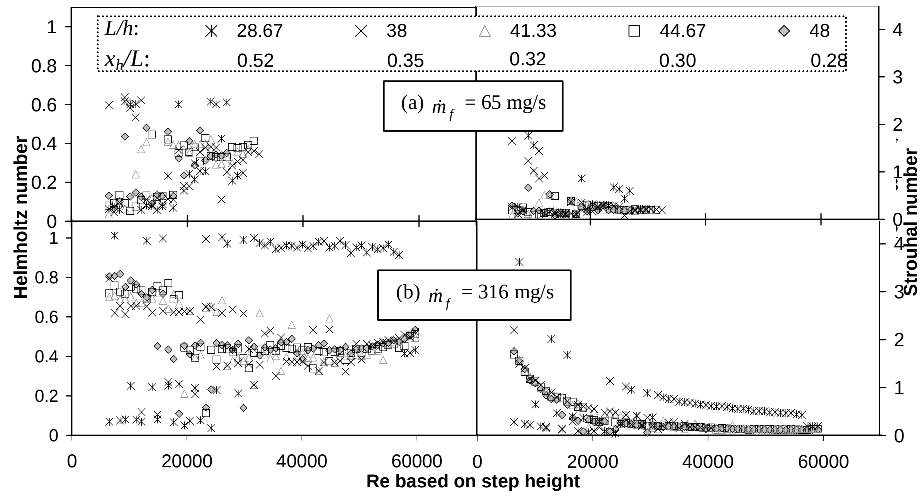


Figure 2 – Helmholtz and Strouhal numbers based on the dominant frequencies observed at the backward-facing step for different fuel flow rates.

Figure 2 shows the variation of the Helmholtz and Strouhal numbers for all duct lengths tested, with the Reynolds number (Re) based on the step height, for sample cases of two extreme fuel flow rates. It can be seen that, even when the fuel flow rate is low, multiple clusters of nearly constant Helmholtz number are recorded, particularly at the low Re range, which converge to a single set of values for all duct lengths in the high Re range. This implies the prevalence of a flow-acoustic lock-on under the above conditions. Since most of the past works were performed mainly under instability conditions, as noted earlier, only the converged set of values were observed, without the need to distinguish them as either natural acoustic modes or vortex shedding modes, by observing variations in the Helmholtz and Strouhal numbers as reported here. Further looking at Figure 2, certain sets of Helmholtz number data are also observed to show linear variation with different slopes that connect the multiple clusters of the low Re range to the single cluster in the high Re range, suggesting that they are vortex shedding modes. This is confirmed by the variation of the Strouhal number, which shows hyperbolic trends of clusters of data asymptoting to constant values as the Re increases, particularly for large duct lengths.

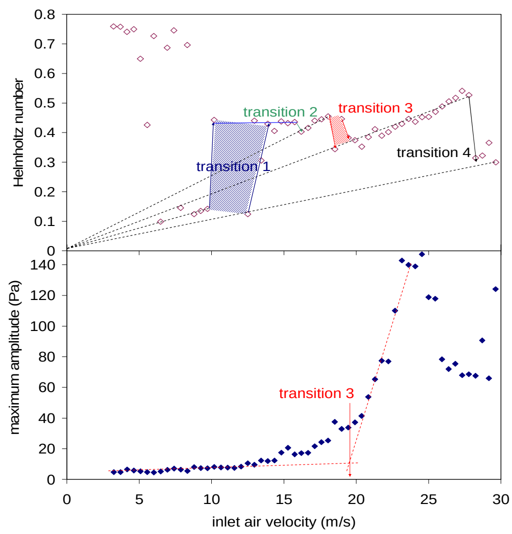


Figure 3 – Mode transitions depicted for L/h = 44.67 and $\dot{m}_f$ = 229 mg/s.

Mode Transitions

The above aspect is investigated in greater detail in Figure 3, which shows a single dataset of Helmholtz number and maximum amplitude variations with air velocity for the case of intermediate values of the fuel flow rate and duct length within the ranges tested. Figure 3(a) shows as many as four transitions; transition 1 occurs in the low velocity range, and marks a jump of the dominant frequencies from vortex shedding modes to an acoustic mode. Further, Figure 3(a) shows what constituted a cluster of several datasets that converged to a single set of Helmholtz number values in the high Re range in Figure 2 to be actually a set of 2-3 stepwise linear variations of the Helmholtz number in that Re range; these are denoted as transitions 2, 3, and 4 in Figure 3(a), which mark shifts in the flow-acoustic lock-on from one vortex shedding mode to another. The different vortex shedding modes are possibly caused by processes such as vortex pairing and merging.

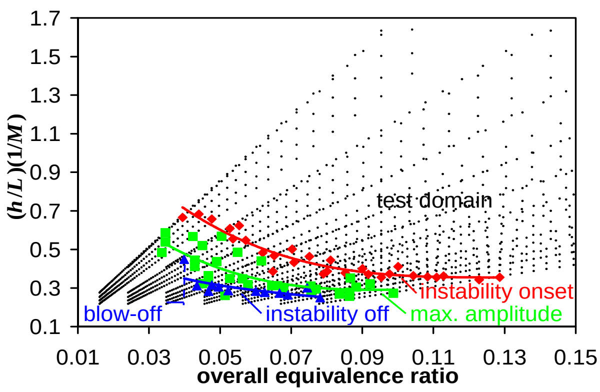
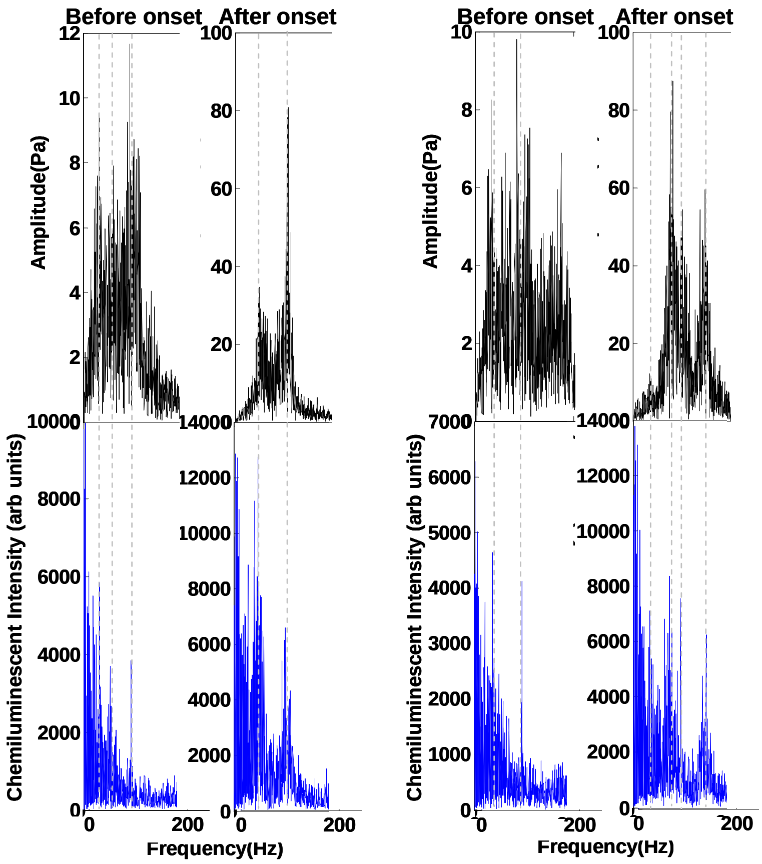


Figure 4 – Conditions for onset of instabili-ty, excitation of maximum amplitude, and instability off.

Onset of Instability

Of the transitions marked in Figure 3(a), transition 3 is quite sharp, and it is also found to coincide with a departure from linearity in the variation of the maximum amplitude, as shown in Figure 3(b). Hence, this transition is taken to mark the onset of acoustic instability in all the datasets examined individually, wherever it is observed. The air flow and geometric conditions corresponding to transition 3 for all the cases tested in the present study are collected together in the form of the ratio of the Strouhal number to the Helmholtz number, $\mathrm{St}/\mathrm{He} = (h/L)(1/M)$, where M is the Mach number of the air flow at the combustor inlet. The above ratio is that of the flow time-scale to the acoustic time-scale in the combustor. Strong flow-acoustic interaction and resonance is expected to occur when this ratio is of the order of $1/n$, where n is the mode number of the natural acoustic mode that is excited due to the combustion. Figure 4 shows this plot for all the conditions tested in the present work, where the value of $(h/L)(1/M)$ is always less than unity, but an appreciable fraction of it. This is due to the fact that the actual length-scales and time-scales in the combustion zone are larger than the characteristic scales taken to form the above fraction.



(a) L/h = 48.00 (b) L/h = 41.33

Figure 5 – Comparison of acoustic and total chemiluminescent intensity spectra.

Chemiluminescence Spectra

Figure 5 shows the comparison of the spectra of acoustic pressure and the total chemiluminescent intensity obtained simultaneously for the two lengths of the duct, with each of which, two conditions, namely, before and after the onset of instability, are presented. The dominant peaks observed in the acoustic spectra are also identified in the total chemiluminescent intensity spectra by means of grey dashed lines in each case. This clearly shows that the chemical heat release rate fluctuations represented by the chemiluminescent intensity fluctuations are responsible for driving the acoustic oscillations. As already noted earlier, some of the frequencies correspond to vortex shedding modes. It is also noted (Fig. 2) earlier that some of the dominant frequencies can be identified as the natural acoustic modes of the duct. The observation of these frequencies in the total chemiluminescent intensity spectra indicates that the natural acoustic modes of the duct influence the vortex shedding process and hence cause heat release fluctuations at those frequencies. The present work shows this interaction to be present even before the onset of instability.

CONCLUSION

The present work has shown that conditions can be identified for the onset of combustion instability by wide variation of flow conditions and appropriate non-dimensionalization of the observed dominant frequencies. The total chemiluminescent intensity fluctuations show the same dominant frequencies as the acoustic oscillations under all conditions, signifying the vortex-combustion interaction prevalent always.

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