Low Frequencies and Growth of Oscillations in a Rijke Tube

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Abstract:

Experiments were conducted in a Rijke tube by varying the surface roughness of the walls, the heat transfer to the air in the tube and by placing a conical horn at the open end of the tube. A sub-harmonic frequency, corresponding to the open end acting partially as a closed end, was shown to be present. Placement of a horn at the open end prevented the tube from sounding. The influence of the roughness of the walls on the pressure oscillations is discussed.

Keywords: Thermo-acoustics, combustion instability, standing waves, Rijke tube.

1. Introduction

The use of lean fuel-air mixtures for gas turbine combustors is associated with the problem of thermo-acoustic instability /1/. A simple way of studying thermo-acoustic instability is by a localized addition of heat in the lower half-portion of a vertically-held cylindrical tube with both ends open which leads to the generation of a loud sound. The tube with the localized heat source is referred to as a Rijke tube and the generation of sound is by the conversion of heat into acoustic energy /2/.

The thermo-acoustic principle contributing to the formation of sound in the Rijke tube is understood well. The natural convection currents from the localized heat release set up acoustic wave motion in the vertically-held tube. The interaction of these acoustic waves with the open ends leads to the formation of a standing wave with pressure nodes at the open ends and a pressure anti-node at the mid-length of the tube /3/. Velocity antinodes are formed at the open ends and a velocity node is formed at the mid length. If positive velocity fluctuations exist at the zone of heat release, enhanced energy is transferred to the medium in the tube leading to the formation of compression waves. The compression waves reinforce the pressure fluctuations in the standing wave and a loud sound is heard /4/. The principle is the Rayleigh criterion which states that "if heat is released at the moment of greatest compression or if it is extracted at the moment of greatest rarefaction", acoustic oscillations are energized /2,4/.

The velocity fluctuations in the upper half of the tube is negative and the heat release here would be out of phase with the pressure fluctuations, with the result that no amplification of the wave motion is possible. Only when the localized heat transfer to the medium in the tube is constrained to the lower half of the tube, can the wave motion grow leading to the generation of a loud noise. Maximum intensification of the wave motion occurs when the heat is transferred to the medium in the tube at the lower quarter length of the tube since the product of the pressure fluctuations and velocity fluctuations in the standing wave is a maximum at this location. Several investigators have exploited the standing wave for improving the heat transfer from

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demonstrated by burning fuel in the zone where heat release augments the pressure fluctuations.

The processes in different combustion devices essentially take place in enclosures partially bounded by walls. The reflection of the incident acoustic wave from the walls of the enclosure and the interaction of the incident wave with the reflected wave could form standing waves in the enclosure. The coupling of the standing wave with the heat release process, as in the Rijke tube, can lead to a drastic increase in the amplitude of pressure oscillations. High amplitude oscillations in combustion equipments are undesirable in that the thermal and mechanical stresses can harm the combustion equipment. The problem, in particular, is of relevance to applications involving very high power densities of heat release such as in chemical rockets and gas turbine combustors and afterburners wherein the large amplitude oscillations would cause a malfunction not only of the propulsive device but of the mission itself. An understanding of the frequencies of the Rijke tube and the damping effects would give inputs for avoiding the incidence of combustion instability in different devices.

The frequencies of the oscillations in Rijke tube have been measured in the earlier investigations /4,6/ and it was shown that the dominant frequencies of the oscillations correspond to the fundamental and higher harmonics of the open-ended tube. Sub-harmonic oscillations corresponding to flame oscillations are seen in the experiments with chemical heat release /6/. Modeling of the excitation of the oscillations has been discussed /7,8/ and methods of actively controlling the noise in the tube demonstrated /9/. The rates of growth and decay of the oscillations have, however, not been explicitly considered with respect to external damping influences. A series of experiments is therefore carried out by varying the damping of the standing waves by the walls and end-boundaries. The experiments are described in section 2. The results are discussed with specific reference to the frequencies and the rate of growth and decay of the oscillations in section 3. The conclusions are summarized in section 4.

2. Experiments

A steel tube 160 cm in length (L) and 10 cm inner diameter (D) was used for the experiments. This would give one-dimensional acoustic waves along the axis of the tube since the length is more than an order of magnitude greater than the diameter. The tube is mounted vertically on a stand as shown schematically in Fig. 1. A series of wire screens (5cm x 5cm) are stacked together and heated to different temperatures using a Bunsen burner. The heated mesh is suspended inside the tube using a wire passing over a pulley fixture above the upper end of the tube. The position of the mesh is varied by releasing or pulling the wire. A measuring scale was fitted to provide the position of the mesh inside the tube.

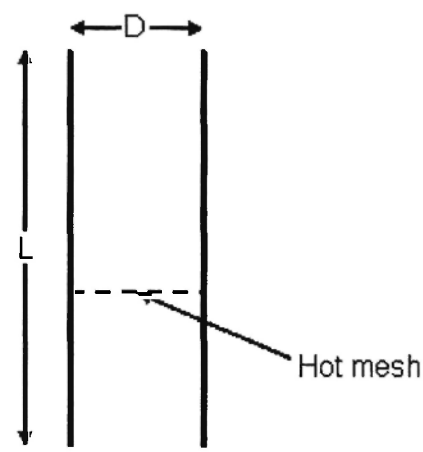

Fig. 1: Schematic of tube with heat release

The hot mesh is positioned at different heights along the length of the tube. The sound, generated in the tube due to the presence of the heated mesh, is recorded using a microphone held above the upper end of the tube. A PCB sensor was used for the calibrating the microphone. A real-time spectral analysis software SIGVIEW was used for analyzing the spectral content of the Sound Pressure Levels (SPL). The mean temperature variation of the mesh with time was recorded using a k-type thermocouple (nickel-chromium). The tip of the thermocouple was embedded in the mesh. The mesh was heated to temperatures up to 300°C.

The walls of the tube were roughened in some of the experiments by placing either perforated Mylar sheets with projections of 0.9 and 1.9 cm or coarse sand paper over the walls. The average spacing between the projections in the Mylar sheet was 3 cm. The coarse sand paper was of P50 Grade corresponding to asperity height of 0.9 mm. The sheets were kept flush over the inner walls of the tube to provide the roughness. Between 12.5 and 50% of the total surface area of the wall was roughened in this way starting from the top open end of the tube. A conical horn was also placed over the top end of the tube in flush with the inner diameter of the tube in a few experiments.

The amplitude of the oscillations and the characteristic frequencies were obtained for the different mesh temperatures and wall conditions.

3. Results and Discussions:

When the heated mesh was placed in the lower half of the tube, SPL gradually increased, reached a maximum value at which it sustained for a short period and then decayed out. A typical plot of the growth, sustenance and decay of oscillations is shown in Fig. 2.

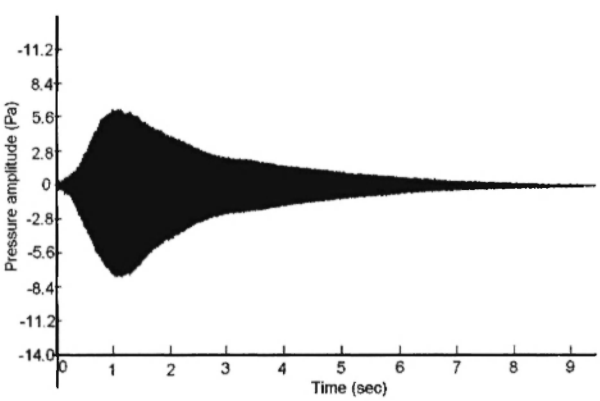

Fig. 2: Growth and decay of pressure oscillations

The SPL during the initial phase of the oscillations and the later part of the decay can be described by the equation /4/:

$$p' = \hat{p}\, e^{\alpha t} \sin \omega t \qquad (1)$$

where $\hat{p}$ is the mean pressure, α is the growth constant in s^{-1} and ω is the circular frequency of the oscillations. Raun *et al.* /4/ have pointed out that as the oscillations grow, α moves out of the linear acoustic region for which Eq. 1 is valid and reaches a limiting value for which the growth constant becomes zero.

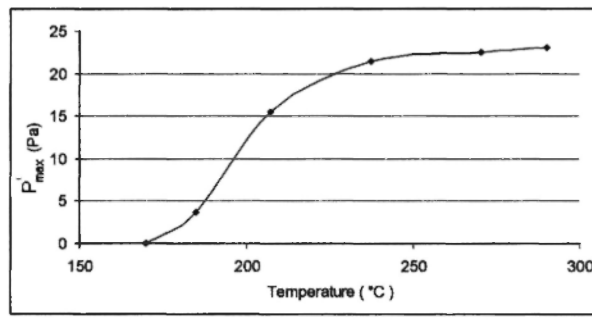

Fig. 3: Maximum sound pressure level obtained with different mesh temperatures

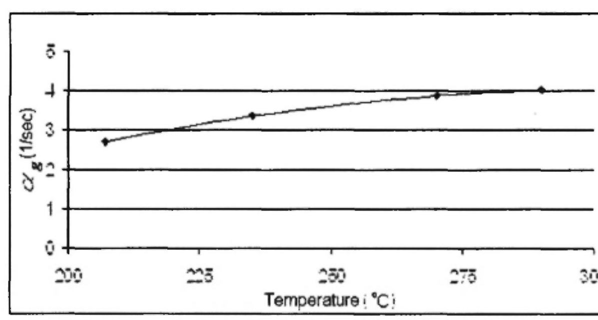

Fig. 4: Growth constant obtained with different mesh temperatures

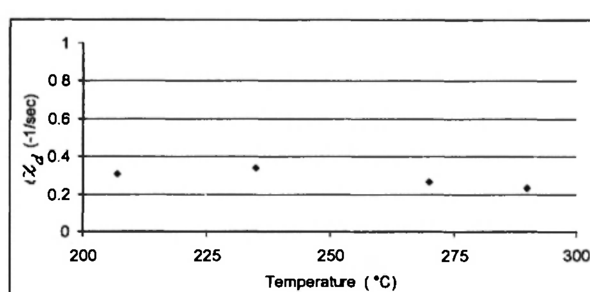

Fig. 5: Decay constant obtained with different mesh temperatures

Maximum SPL and maximum growth constants were obtained when the mesh was placed at a distance of quarter length of the tube from the lower end as observed by other investigators /2,4/ and in agreement with theory /2/. When the mesh was heated to different temperatures and placed at this position, it was observed that the maximum value of SPL increased with increase in mesh temperature. The variation of the maximum SPL is shown in Fig. 3. It is seen that the maximum SPL increases more significantly with temperature when the temperature of the mesh is small and the rate of increase rapidly drops off as the mesh temperature is about 240°C. It is also seen from Fig. 3 that a minimum temperature of about 170°C is required for the oscillations to occur i.e., the sound to be generated.

3.1 Threshold temperature for sounding of tube and saturation of SPL

The implications of the existence of a threshold temperature for exciting the oscillations and the trend towards saturation in the sound pressure levels with increase of the mesh temperature is better understood by examining the growth constant (α_g) during the initial period of growth and the decay constant (α_d) obtained during the end of the oscillations when the contribution of the heated mesh would be negligible. Figures 4 and 5 show the growth and decay constants obtained in the different experiments with varying temperatures of the mesh. It is seen that while α_g increases with increasing mesh temperature (giving a trend similar to that obtained for maximum SPL in Fig. 3), the decay constant (α_d) remains nearly constant at magnitudes which are one order of magnitude smaller.

Damping effects are invariably present during the growth phase of the oscillations. The actual or true growth constant from the energy release is therefore:

$$\alpha = |\alpha_g| + |\alpha_d| \tag{2}$$

A plot of the true growth constant α as a function of the initial temperature is given in Fig. 6 and is seen to increase with increase of temperature. The incremental change of growth constant with change of temperature comes down as the temperature increases.

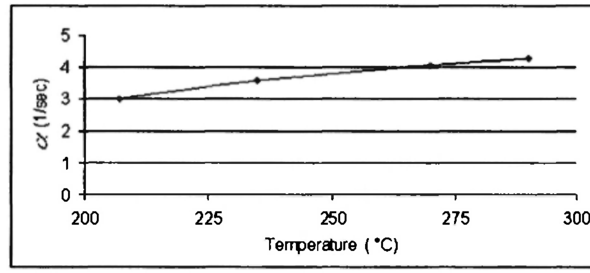

Fig. 6: Variation of net growth constant with temperature of the mesh

The growth constant α is given by the ratio of rate of heat addition to the wave motion $\dot{E}$ and twice the mean acoustic energy $\bar{E}$ in the medium ($\alpha = \dot{E}/2\bar{E}$). The mean acoustic energy in the medium $\bar{E} = p'^2/\rho C$ where p' is the pressure amplitude and ρC is the acoustic admittance of the medium. The acoustic admittance of the medium air in the tube does not change significantly. $\bar{E}$ would increase with increase of the mesh temperature due to the higher pressure amplitudes of the wave motion obtained at the higher mesh temperatures. The rate of energy going into wave motion $\dot{E}$ would also progressively increase with increase of temperature since the heat transfer coefficient is higher with the increase of the pressure amplitude p' and an increase in the temperature difference between the mesh and the gas medium would augment the heat transfer. The value of α should therefore increase with increase of the pressure perturbations which is contrary to the experimental observation. The energy driving the wave motion $\dot{E}$ obviously decreases as p' increases. It has been suggested /4/ that the phase difference between heat transfer and velocity fluctuation would decrease as the velocity amplitude increases. This would make the heat transfer to be out of phase with the pressure perturbation resulting in a reduced value of $\dot{E}$.

The existence of the minimum threshold value of temperature for obtaining oscillations (170°C) would be the requirement to supply sufficient $\dot{E}$ in order to overcome the factors responsible for dissipation of the waves. The dissipation or damping is brought about by the acoustic boundary layer losses at the tube walls, sound radiation from the open end of the tube and convection of sound. Experiments were done by varying the losses at the walls using different levels of roughness or protrusions covering between 15 to 50% of the cylindrical walls but keeping the energy driving the oscillation constant. This was done by keeping the initial mesh temperature at a specified value and positioning the mesh at the lower quarter length distance. The roughness was obtained by introducing protrusions of 9 and 19 mm spaced 30 mm apart and by placing a coarse sand paper having asperity heights of 0.9 mm over the wall surface. The results are shown in Fig. 7. The decay constant (α_d) is seen to increase with increase in the level of surface roughness and with the fraction of the tube surface roughened.

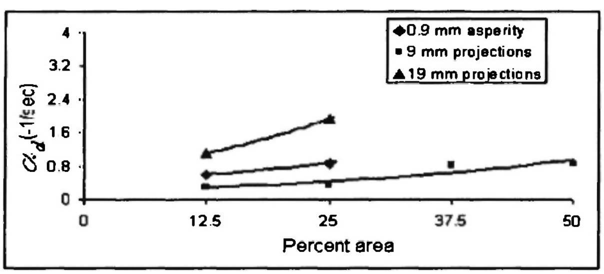

Fig. 7: Variation of decay constant with surface roughness

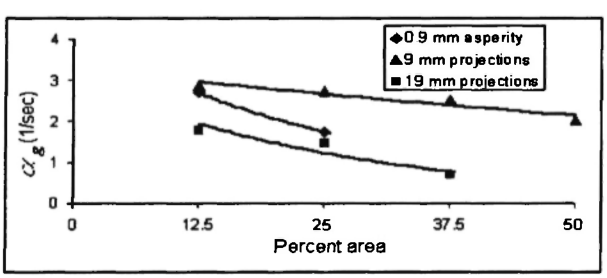

Fig. 8: Variation of growth constant with surface roughness variations

The growth constant (α_g) for the above levels of roughness of the tube, when the heated mesh at a constant temperature of 190°C was placed at the lower quarter length of the tube, is shown in Fig. **8**. It is seen that the growth constant decreased with increase of surface roughness and the fraction of the surface roughened. Growth of oscillations was not possible when the roughened surfaces comprising 19 mm projections covered more than about 25% of the surface and 9 mm projections covered about 37.5% of the surface. The true growth constant α, however, remained nearly the same for the different levels of surface roughness of the tube and this is shown in Fig. 9, suggesting that the energy driving the oscillations has remained the same. The mechanisms dissipating the wave motion in the tube are seen to contribute to the existence of a threshold temperature of the mesh for sounding the tube.

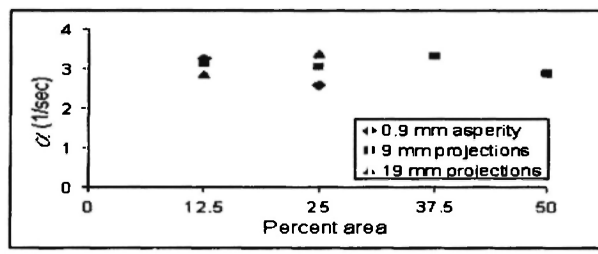

Fig. 9: Variation of the true growth constant

3.2 Sounding of tube with a conical horn mounted at top open end

A conical horn placed at the top open end would help in focusing the sound generated by the tube giving a higher SPL along the axis of the tube. However, the conical horn, if placed in flush with the inner diameter at the exit, would also allow the incident waves to radiate out making the formation of standing waves in the tube impossible. Experiments were done by mounting a conical horn at the top end of the tube. Whatever be the temperature of the mesh and the position of the mesh, it was found impossible to sound the tube in the presence of the conical horn. The importance of generating a standing wave in the tube is the fundamental requirement for the formation of the heat- induced oscillations. Partial blocking of the open end which also led to disruption of the standing wave in the tube has been shown to inhibit the tube from sounding /4/. The importance of shaping a combustion chamber to prevent the incidence of combustion instability by eliminating the formation of standing waves is demonstrated through this experiment.

3.3 Lower frequencies of oscillation at higher heat transfer rates:

Chatterjee *et al* /6/ have recently addressed the spectral characteristics of the Rijke tube and find sub-harmonic resonance at about half the frequency of acoustic forcing. They suggest that the low frequency comes from flame oscillations. The present set of experiments does not have the flame driving the oscillations. At higher values of the temperature of the mesh, a lower frequency of 48 Hz which is a sub-harmonic of the fundamental was observed. The amplitude at this frequency is very predominant and is shown in the waterfall plot in Fig. 10.

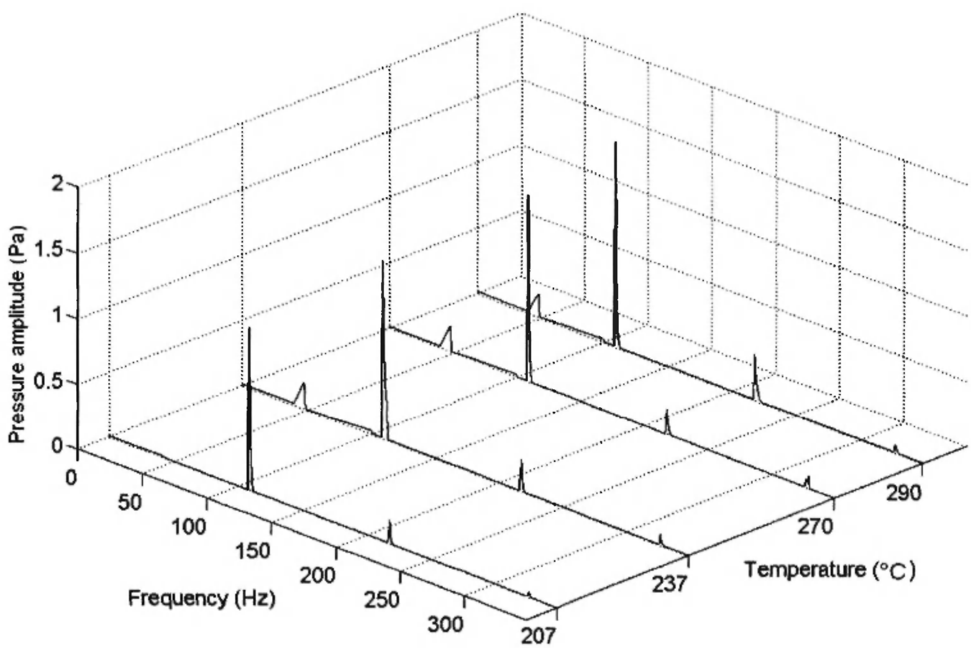

Fig. 10: Characteristic frequencies at different values mesh temperature

The present experiments do not contain a flame and yet the sub-harmonic content is seen. It appears likely that the plume from the increased advection of gases at the higher values of mesh temperatures may lead to relatively steeper gradients just above the tube wherein the rising plume mixes with the ambient. Part of the wave motion then corresponds to a tube closed at this position of the changing properties and open at the lower end. One needs to consider the likely formation of such lower frequencies in combustion instability in practical devices.

4. Conclusions:

Experiments were done to determine the sounding of a Rijke tube with walls of different roughness levels and different values heat release. A threshold value of heat transfer is seen necessary to overcome the inherent damping present in the tube and make the tube sound. Low frequency oscillations are shown to be obtained for which the open end acts as partially closed due to the gradients in the rising plume of gases. Incorporation of a conical horn inhibits sounding of the Rijke tube. The study shows the importance of shaping of combustion chambers to prevent the incidence of combustion instability.

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