

LETTERS TO THE EDITOR

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Characteristics of thermoacoustic resonance in a ducted burner

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Combustion instability accompanied with low-frequency oscillations is one of the typical phenomena in a ducted flame burner. This is due to the interaction between unsteady heat release and the sound pressure field known as thermoacoustic feedback. A parametric study was carried out through measurements of acoustic pressure and flame radiation at various conditions not only to elucidate the effect of Reynolds number and equivalence ratio on thermoacoustic oscillation, but also to understand the mechanism of the onset of thermoacoustic resonance in a ducted flame burner. The results explain that equivalence ratio has significant effects on the magnitude of pressure and heat fluctuation as well as the fundamental frequency. It is also found that the onset of thermoacoustic resonance is strongly affected by the interacting mechanism between acoustic energy and heat release. © 1999 Acoustical Society of America. [S0001-4966(99)03306-8]

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INTRODUCTION

Thermoacoustic oscillation is one of the typical phenomena in a ducted flame burner, and is usually accompanied with severe vibration and noise. This low-frequency oscillation with high amplitude can result in structural damage or deterioration of the performance of the subsidiary system. Thus the understanding of physics in thermoacoustic oscillation has great importance in both combustor design and noise control.

Different from turbulent combustion noise, the spectrum of the thermoacoustic oscillation shows discrete frequency behavior. The noise is mainly caused by the interaction between the unstable heat release and the sound field—which is called thermoacoustic feedback. If the energy release by combustion and the pressure fluctuation are in phase, thermodynamic and acoustic energy are fed to each other and then the amplitude of oscillation increases remarkably. Rayleigh¹ explained that thermoacoustic resonance occurs if the Rayleigh index becomes positive. The Rayleigh index $G(x)$ can be expressed as

$$G(x) = \frac{1}{T} \int_T q'(x,t)p'(x,t)dt, \quad (1)$$

where T is the instability period, q' is the unsteady heat release, p' is the pressure fluctuation, x is the axial location, and t is the time. Although many papers^{2–6} concerning this

phenomenon have already been published, some fundamental questions regarding the effects of flow and combustion parameters on the onset of thermoacoustic resonance still remain to be investigated. For example, Heito *et al.*⁶ found that the equivalence ratio has a crucial effect on the onset of oscillation, but no further explanation about the relationship between equivalence ratio and heat release or pressure fluctuation was given. Understanding the onset of thermoacoustic resonance requires detailed measurements of acoustic pressure and unsteady heat release with variations of physical parameters. Therefore, in the present study, a parametric study was carried out through measurements of acoustic pressure and flame radiation at various conditions, to elucidate the effect of physical parameters, such as Reynolds number and equivalence ratio, on the onset of thermoacoustic oscillation in a ducted premixed flame burner.

I. BRIEF DESCRIPTION OF EXPERIMENT

A schematic sketch of the experimental setup to simulate thermoacoustic oscillation is shown in Fig. 1. It is a Rijke-type burner with a premixed flame across the entire cross section in the lower half (approximately at the quarter position) of the pipe having a diameter of 60 mm. The total length of the pipe was 1 m, and a short quartz pipe was installed at the location of the flame to observe flame oscillation and measure the light emission. Bundles of fine stainless steel pipes 2 mm in diameter were used for a flow straightener as well as flame holder. A decoupling chamber (60l) was installed for stabilizing airflow and for sufficient

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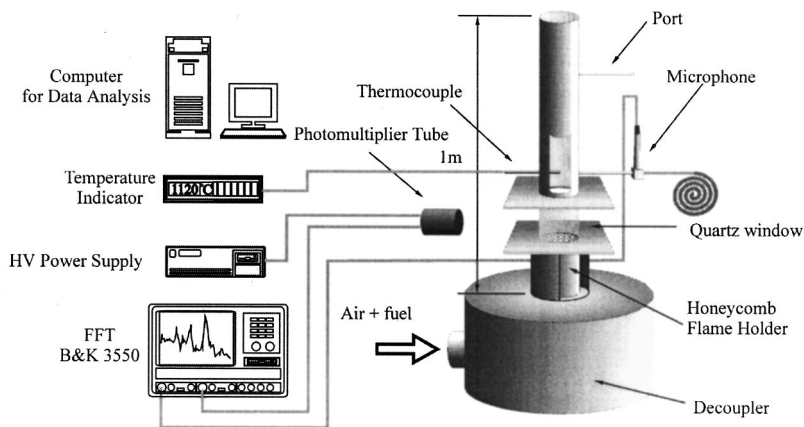


FIG. 1. Schematic sketch of the experimental setup.

premixing of the fuel (propane) and oxidizer. Sound pressure level was measured by a B&K 4134 condenser microphone located at the middle of the pipe. Since the temperature of the pipe was so high, an acoustic waveguide was utilized instead of flush mounting of the microphone to the wall of the tube. The acoustic signal measured by the sensor was transferred via a preamplifier to a B&K 3550 FFT analyzer. A thermocouple was also installed to measure the time-averaged (mean) temperature at the same time.

In the combustion region, there exist light emissions from free radicals. Among them, C_2 light emission intensity from the flame can be interpreted as an extent of unsteady heat release.^{7,8} To measure the C_2 emission intensity only, a Hamamatsu R943-02 photomultiplier tube (PMT) was utilized with an optical filter, whose peak transmission wavelength is 516.4 nm.

II. RESULTS AND DISCUSSION

Figure 2 shows the pressure spectra of acoustic oscillation as a variation of Reynolds number at a fixed equivalence ratio of $\Phi=1.0$. The measured fundamental frequency was far from the theoretical value ($f_c = c/2L$) evaluated approximately with the geometry and a given temperature, which implies that this phenomenon is obviously nonlinear.

The largest magnitude of oscillation was obtained for the fundamental mode, and was over 20 dB stronger than the following higher harmonics. With a limited variation of Rey-

nolds number (from 3000 to 9000 due to the limitation of the burner capacity), the magnitudes of pressure peaks were not very sensitive to the flow rate. The broadband noise increased slightly by turbulence as Reynolds number increased, and as a consequence, total sound pressure level increased by 1–2 dB.

Figure 3 shows the variation of the mean temperature (time-averaged temperature measured by a thermocouple at the middle of the pipe) at the onset of strong thermoacoustic oscillation with respect to equivalence ratio ($\Phi=0.8-1.6$). This figure clearly shows that at lean mixtures the oscillation starts at relatively higher mean temperatures than at rich mixtures. In the process of initiating a resonant oscillation, the mean temperature should be raised to a minimum (or threshold) value as shown in Fig. 3. To understand the detailed mechanism, the time traces of the pressure spectra during the process of starting a resonance were measured as shown in Fig. 4. For a lean mixture ($\Phi=0.8$), resonance started at a relatively higher mean temperature (about 1000 °C at $L/2$). With an onset of oscillation, the mean temperature suddenly dropped down to 750–800 °C, and then recovered again until a terminal mean temperature was attained. During this process, the fundamental frequency and its harmonics also suddenly shifted down and came back, as shown in Fig. 4(a). Before the thermoacoustic resonance initiated, there existed weak tonal noise (at least 30 dB weaker than in the resonance case). In this case, flame oscillations

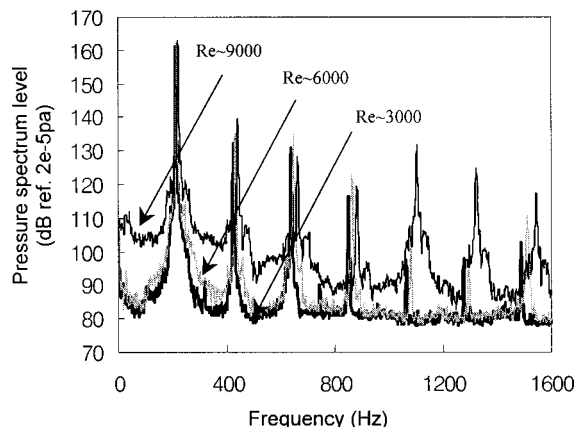


FIG. 2. Pressure spectra at the middle of the pipe ($\phi=1.0$).

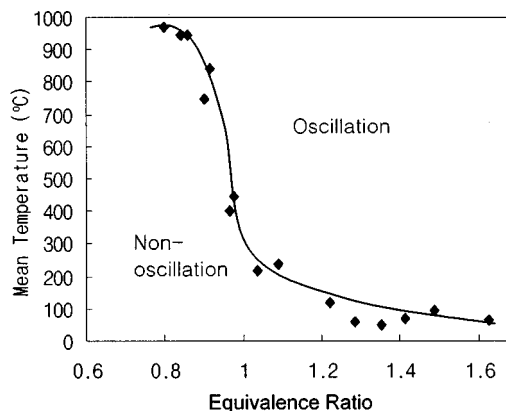


FIG. 3. Resonance-starting mean temperature at the middle of pipe with respect to equivalence ratio.

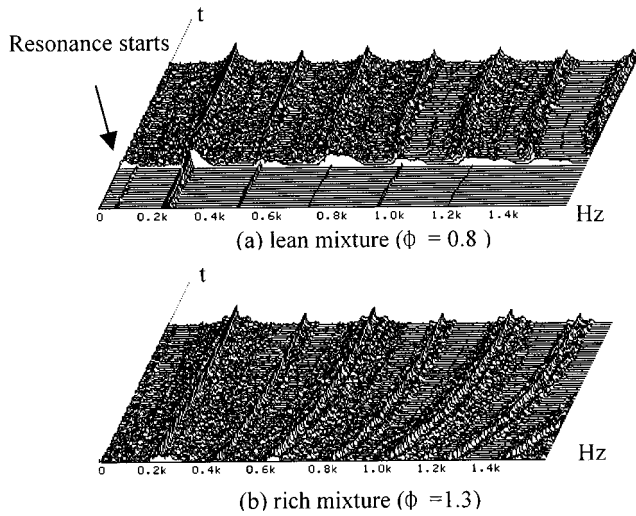


FIG. 4. Time histories of pressure spectra during resonance-starting process (time step: 0.5 s).

and PMT signals are rarely observed, therefore, it can be regarded as a transient state rather than a driving state.

As the equivalence ratio increased, the mean temperature required for the development of oscillations decreased rapidly. Since the resonance-starting temperature was relatively low for a rich mixture ($\Phi=1.3$), no temperature drop was found in this range. As shown in Fig. 4(b), frequencies of pressure spectra shifted up monotonously with a temperature rise. The above results explain that the mechanism of an onset of thermoacoustic oscillation is strongly affected by equivalence ratio. It is also worthwhile to note that a critical requirement for the development of thermoacoustic oscillation is that the heat energy should be sufficient to overcome the energy loss from the system. At a lean mixture, the energy gain through the cycle is smaller (than at a rich mixture) since heat release is smaller. Therefore, the lean mixture case takes more time to reach the critical energy level to excite a resonant oscillation. Consequently, the oscillation-starting temperature of a lean mixture is higher than that of a rich mixture case. From Fig. 4, one can notice that, at a lean mixture, the system needs an additional energy shift from heat energy to excite resonance at an earlier stage of oscillation. This is the reason that the temperature (frequency) decreased at first, then increased again as the system gained energy. On the other hand, in the rich mixture case, the system did not need a shift from heat energy to mechanical energy for exciting a resonance since the system already had a sufficient amount of energy.

To verify this idea, the unsteady heat release was also measured since C_2 emission intensity can be interpreted as an index of unsteady heat release. Results of microphone and photomultiplier measurements are shown in Fig. 5(a). It confirms that the two signals oscillate with the same fundamental frequency and its harmonics. Figure 5(b) shows the variations of unsteady heat release, pressure fluctuation, and Rayleigh index with respect to equivalence ratio. To calculate the Rayleigh index $G(x)$ from the measurements, the integral of Eq. (1) has been expressed in the frequency domain:

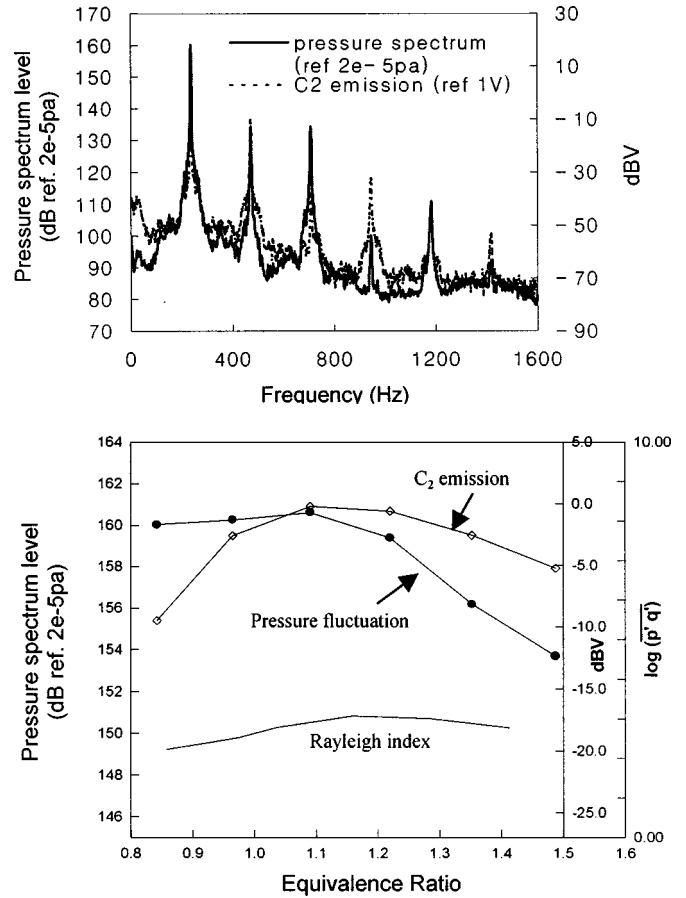


FIG. 5. (a) Spectra of pressure fluctuation and C_2 emission rate ($\phi=1.0$). (b) Variation of pressure fluctuation, C_2 emission, and Rayleigh Index with respect to equivalence ratio.

$$G(x) = \int |S_{pq}| \cos \theta_{pq} dV. \quad (2)$$

In this equation, S_{pq} and θ_{pq} are the cross spectrum and phase difference between the pressure and heat release, respectively, and the V is the volume of the flame.

Heat release was relatively small for a lean mixture, whereas the pressure fluctuation is large. It showed a reversed tendency for the rich side. In other words, pressure fluctuation is more dominant than heat fluctuation for a lean mixture, whereas heat fluctuation is more dominant for a rich mixture. This is a slightly surprising result because, in a lean mixture, a higher sound pressure was obtained in spite of smaller heat release than at a rich mixture. It could be explained as follows: the system energy gain is a product of pressure fluctuation and unsteady heat release. With a fixed condition, the total energy gain or Rayleigh index should be maintained at almost a constant value. Otherwise, the system gains more energy until it bursts (the index keeps increasing) or loses energy to be out of resonance (the index keeps decreasing).

III. CONCLUSIONS

The results of this study are summarized as follows:

- (1) The Reynolds number is not a sensitive parameter for both the maximum pressure peak and the fundamental

frequency of thermoacoustic oscillation in a Rijke-type burner. On the other hand, equivalence ratio has a strong effect on the maximum pressure fluctuation and the fundamental frequency of thermoacoustic resonance.

- (2) To initiate a thermoacoustic resonance, a certain level of system energy should be required. This is why, for a lean mixture, oscillation starts from a higher mean temperature (than at a rich mixture) and then a sudden temperature drop exists in its initial phase of thermoacoustic resonance.
- (3) The product of acoustic pressure fluctuation and unsteady heat release (the Rayleigh index) should be maintained in the thermoacoustic resonance process.

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¹A. P. Dowling, and J. E. Ffowcs Williams, *Sound and Sources of Sound* (Ellis Horwood Limited, Chichester, 1983).

²G. J. Bloxidge, "Reheat buzz. An acoustically driven combustion instability," Ph.D. Thesis, Cambridge University (Cambridge, England, 1987).

³M. Fleifil, A. M. Annaswamy, Z. A. Ghoneim, and A. F. Ghoniem, "Response of a laminar premixed flame to flow oscillation. A kinematic model and thermoacoustic instability results," *Combust. Flame* **106**, 487–510 (1996).

⁴P. J. Langhorne, "Reheat buzz. An acoustically coupled combustion instability. Part 1. Experiment," *J. Fluid Mech.* **193**, 417–443 (1988).

⁵U. G. Hedge, D. Reuter, and B. T. Zinn, "Sound generation by ducted flames," *AIAA J.* **26**, 532–537 (1987).

⁶M. V. Heito, A. M. K. P. Taylor, and J. H. Whitelaw, "Influence of confinement on combustion instabilities of premixed flames stabilized on axisymmetric baffles," *Combust. Flame* **57**, 109–121 (1984).

⁷B. N. Shivashankara, W. C. Strahle, and J. C. Hardley, "Evaluation of combustion noise scaling laws by an optical technique," *AIAA J.* **13**, 623–627 (1975).

⁸I. R. Hurlle, R. B. Price, T. M. Sugden, and A. Thomas, "Sound emission from open turbulent premixed flame," *Proc. R. Soc. London, Ser. A* **303**, 409–427 (1968).