Applied Energy 182 (2016) 320–330

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental and numerical definition of the extreme heater locations in a closed-open standing wave thermoacoustic system

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HIGHLIGHTS

- Experimental studies of the most ‘dangerous’ heater location are conducted.
- Nonlinearity is identified experimentally.
- Transient energy growth and modal analyses are performed.
- Good agreement is obtained between experimental and theoretical results.
- Rayleigh index is determined as an indicator of the heat-to-sound coupling.

ARTICLE INFO

Article history:
Received 1 July 2016
Received in revised form 12 August 2016
Accepted 17 August 2016
Available online 28 August 2016

Keywords:
Energy conversion
Thermoacoustic oscillations
Combustion instability
Thermoacoustic instability
Transient growth
Standing wave

ABSTRACT

In this work, experimental study of a close-open standing-wave thermoacoustic system with a heat source confined is performed first. By varying the axial location x_f/L of the heat source, the thermoacoustic oscillation intensity is experimentally shown to be varied. Maximum-amplitude oscillations occur, as the heat source is axially placed at $0.4 \leqslant x_f/L \leqslant 0.55$. This indicates that the most ‘dangerous’ axial location of the heat source is close to the middle of the combustor. Furthermore, time-frequency analysis of the measured pressure signal reveals that the thermoacoustic system is nonlinear due to the presence of comparable amplitude peaks in the spectrum. To gain insights on the most ‘dangerous’ axial location and nonlinearity, and to validate our experimental findings, a 1D model of a closed-open standing-wave thermoacoustic system is developed. The effects of (1) the heat source location x_f/L, (2) the number of eigenmodes N and (3) the mean temperature ratio T_2/T_1 across the heat source on the dynamics and transient stability behaviors of the standing-wave system are examined one at a time. It is found that the most ‘dangerous’ axial location of the heat source is approximately at $x_f/L = 0.5$. This is in good agreement with the results from our experimental measurement and the conventional modal analysis. In addition, it is shown that the most ‘dangerous’ heat source location is shifted by varying the downstream mean temperature. Similar finding is experimentally observed. Finally, Rayleigh index as an important stability indicator is defined and calculated to characterize the heat-to-sound coupling. The present work opens up new applicable way to produce maximum-amplitude standing-wave thermoacoustic oscillations in a practical engine system.

1. Introduction

In order to increase combustion efficiency and to meet more stringent combustion emission requirements, lean premixed combustion technology is currently widely applied in gas turbines, aero-engines or other engine and propulsion systems [1,2]. However, this combustion technology is often associated with self-sustained nonlinear thermoacoustic oscillations (also known as thermoacoustic instability) [3,4]. Such thermoacoustic oscillations are characterized by large-amplitude ‘tonal noise’ [5–7]. These flow oscillations are wanted in thermoacoustic Stirling heat engines or cooling systems [8–11]. However, they are unwanted in many propulsion systems such as rocket motors and aeroengine

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http://dx.doi.org/10.1016/j.apenergy.2016.08.104
0306-2619/

afterburners, since the flow oscillations may be intense that they can cause overheating, structural vibration, or mechanical fatigue [12–17].

On a laboratory-scale, self-excited thermoacoustic oscillations are often observed in closed-open [13,18] or open-open thermoacoustic combustors [13,19]. Typically, an acoustically compact heat source such as a premixed or diffusion flame [20,21] or an electrical heater is confined in the combustion systems. Chatterjee et al. [18] conducted experimental studies to investigate the onset of thermoacoustic oscillations in a closed-open combustor with a length of 1.524 m. A methane-burned premixed flame is anchored at the middle of the combustor. Such thermoacoustic system is found to be associated with the 2nd eigenmode being excited and lower-frequency pulsating instability. The closed-open thermoacoustic system is corresponding to Neumann and Dirichlet boundary conditions. And it is analogy to the physical configuration of a standing-wave thermoacoustic heat engine system.

Open-open thermoacoustic systems are well-known as Rijke tubes. Such systems have been investigated extensively [13,22,23] in laboratories, which are nonlinear and non-normal. The non-normality indicates that small acoustic perturbations in the combustors may exhibit large transient energy growth [21]. If the transient growth is quite large, thermoacoustic instability might be triggered from initial small-amplitude flow disturbances. To analyze the role of non-normality, a simple 1D model of a thermoacoustic combustor with both ends open were developed [22]. For convenience, the mean temperature across the heat source was assumed to be the same, although it was not experimentally justified [4]. The modelled combustor in Ref. [5] was then used by Juniper [24] to determine the most ‘dangerous’ initial state that could trigger self-sustained thermoacoustic oscillations. The same modelled combustor was then used to examine the noise effect on triggering thermoacoustic instability [24]. It was found that pink noise (higher amplitudes at low frequencies) was more effective than other types (such as white and blue) of noise in triggering thermoacoustic oscillations.

To generate maximum-amplitude thermoacoustic oscillations, theoretical and experimental investigations on the effect of the axial location of a heat source are conducted on open-ended systems [23]. Carvalho et al. [23] used a basket of burning wood as a ‘heat source’ to excited thermoacoustic oscillations in a tube with length $L \approx 3.0$ m. They found that the maximum-amplitude oscillation occurred, when the ‘heat source’ was placed at $L/4$ with respect to the bottom open end for the fundamental mode, and $L/8$ and $5L/8$ for the second harmonic modes. Similar findings were theoretically obtained by Collyer and Ward [25]. By now, the effects of the axial location of a heat source and the mean temperature gradient across the heat source on eigenmodes frequencies in closed-open thermoacoustic systems have not been examined. Neither have the effects of the heat source location and the mean temperature gradient on transient energy growth analysis of such close-open standing-wave thermoacoustic systems. Lack of these investigations partially motivated the present work.

In this work, experimental measurement of a closed-open standing wave thermoacoustic combustor is performed first. This is described in Section 2. The effects of the axial location of the heat source and the fuel flow rate are investigated. The most ‘dangerous’ location of the heat source corresponding to the maximum-amplitude sound is experimentally determined. To simulate the experiments and gain insights on the extreme axial location of the heat source, a thermoacoustic model of a closed-open standing-wave system is developed. This is described in Section 3. Unsteady heat release from an acoustically compact heat source is modelled by using a modified King’s law, which can be linearized into the classical $\mathcal{N}-\tau$ (time-lag) formulation [22,24]. And the acoustic disturbances are expanded using Galerkin series [22,24]. The influences of the heat source location and the mean temperature ratio across the heat source on the eigenmodes frequencies are discussed and compared with those in the absence of mean temperature ratio. In Section 5, the ‘extreme’ heater locations in triggering thermoacoustic instability are predicted by calculating the maximum transient growth of acoustical energy. Comparison is then made between the present measurements, transient energy growth and classical modal analyses [23,25].

2. Experimental study

Experiments measurements are conducted on a closed-open thermoacoustic combustor, as shown in Fig. 1. Its length and inner diameter are 800 and 75 mm respectively. A premixed methane-burned flame is confined in the tube at x_f. Similar configuration of closed-open thermoacoustic combustor is studied by Chatterjee et al. [18]. A B&K type 4977 microphone is used to measure the pressure signal to determine the thermoacoustic oscillation spectrum. The sampling rate is 5000 samples per second. The measured time evolution of the spectrum is shown in Fig. 2.

It can be seen that there are 2 dominant frequencies at 161 Hz and 240 Hz. This indicates that the standing-wave thermoacoustic system is nonlinear.

As the heat source’s axial location is varied, the pressure fluctuations are measured. The variation of the root mean square (RMS) of the pressure oscillations with the axial location of the heat source is illustrated in Fig. 3, as the methane flow rate $\dot{m}_f$ is set to 2 different values. Note that for each given $\dot{m}_f$, the pressure RMS values are measured twice (i.e. 1st and 2nd tests) for our measurement repeatability.

It can be seen from Fig. 3(a) that as $\dot{m}_f$ is set to 2.2 L/min, as the heat source location x_f/L is increased from 0.2 to 0.7 (i.e. test 1), the pressure oscillations are intensified. Further increasing x_f/L leads to p_{rms} being decreased. The maximum p_{rms}^{max} occurs near $x_f/L \approx 0.43$. This axial location is known as the most ‘dangerous’

Fig. 1. Photo of a closed-open standing-wave thermoacoustic combustor with a total length of $L = 800$ mm.