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Entropy-involved energy measure study of intrinsic thermoacoustic oscillations

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HIGHLIGHTS

- Entropy-involved energy measure is defined to study intrinsic thermoacoustic oscillations.
- Effects of mean flow, flame transfer function and entropy waves are examined.
- Cases studies are performed in premixed combustors with transfer or describing functions.
- Stability of intrinsic thermoacoustic modes is predicted by calculating critical gain.
- Frequencies and critical gain of intrinsic modes depend on mean temperature ratio.

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ABSTRACT

It is conventionally believed that there are no self-sustained thermoacoustic oscillations in the absence of acoustic modes in combustors. However, such oscillations (also known as intrinsic thermoacoustic instability) are recently found to occur in a premixed combustor with a mean flow present but no acoustic eigenmodes involved. Practical combustors are associated with entropy waves, pressure jump and mean flow, which are ignored in previous studies without justification. In this work, an entropy-involved energy measure is defined and used to study the stability behaviors of intrinsic thermoacoustic modes. The concepts and methods are exemplified with the classical time-delay $n-\tau$ unsteady heat release model. The intrinsic thermoacoustic eigenmodes are found to be related to not only a flame transfer/describing function but also the acoustic impedance at the flame, which is boundary-dependent. It is shown that the predicted frequency ω_f^r of the intrinsic modes and the critical gain n_c depend on the ratio $\bar{T}_2/\bar{T}_1$ between the after- and before-combustion temperatures and the inlet mean flow Mach number $\bar{M}_1$. Comparison is then made between the present results and those available in literature. Good agreement is obtained for ω_f^r. Furthermore, the predicted stability of intrinsic modes based on calculated n_c is found to agree well with direct numerical simulations (DNS). It is also interesting to show that as $\bar{T}_2/\bar{T}_1 \to 1$, the critical gain as predicted from the previous models is $n_c \to +\infty$, which means that all intrinsic eigenmodes are stable. However, the present works shows that $n_c \to 1.0$. Further illustration is then performed by conducting case studies of measured flame transfer and describing functions in premixed combustors. The present work opens up an alternative but more applicable way to study intrinsic thermoacoustic oscillations via the entropy-involved energy measure.

1. Introduction

Thermoacoustic instability [1–4] is of particular current concern due to its frequent occurrence in the new generation of gas turbines [5,6] and aeroengines, in which reducing emission is a priority. Thermoacoustic instability most often arises due to a coupling between acoustic disturbances and unsteady heat release [7–9]. Unsteady combustion is an efficient sound source and combustors tend to be highly 'acoustic resonant' systems [10–14]. Typically, when thermoacoustic instability occurs, an acoustic mode of the combustor is excited. However, recent theoretical studies [15–17], DNS [18,19] simulations and experiments [20] reveal that thermoacoustic instability may occur, even in an anechoic environment. These unstable modes characterize 'intrinsic instability', which is associated with no acoustic waves reflected

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back from the boundaries of the combustor due to the impedance change [21,22]. These 'intrinsic' modes do not depend on the acoustic mode corresponding to the combustion system. They are excited by a feedback mechanism inherent [15–17] to the flame and its surrounding flow conditions.

Intrinsic thermoacoustic instability (ITI) has been first investigated experimentally [20] and theoretically [15–17] in premixed combustors. For simplicity, the cross-sectional area of the combustor is assumed to be invariant, and the mean flow effect is neglected in the theoretical models [15–17]. The unsteady heat release and acoustic disturbances are coupled by using 'acoustic Rankine–Hugoniot jump conditions' [23]. A scattering matrix is built from a flame transfer function [24–28] $F(\omega) = (\hat{Q}(\omega)/\bar{Q})/(\hat{u}(\omega)/\bar{u})$ and used to characterize the intrinsic thermoacoustic eigenfrequencies from its poles [15–17]. Here $\hat{Q}(\omega)$ and $\hat{u}(\omega)$ are Fourier transform of unsteady heat release rate $Q'(t)$ and oncoming flow velocity $u'(t)$. $\bar{Q}$ and $\bar{u}$ are the mean heat release and velocity. These poles coincide with the eigenmodes of the flame-intrinsic feedback interaction [15–17]. The intrinsic modes may result in thermoacoustic instability without locking onto one of the acoustic eigenmodes of the combustor. One of the interesting questions about the previous theoretical model is that it predicts that all intrinsic modes are stable, when the mean temperature ratio $\bar{T}_2/\bar{T}_1 \leqslant 3$. This is due to overprediction of critical gain $F_c > 1.6$ or $n_c > 1.6$, which is higher than measured transfer function gain [18].

To further validate the theoretical and experimental findings on intrinsic thermoacoustic instability, direct numerical simulations (DNS) [18,19] of a premixed laminar flame have been recently conducted. Courtine et al. [18] numerically studied the intrinsic thermoacoustic instability in 5 combustors with different cross-sectional area and length ratios between upstream and downstream duct. The numerical results are then compared with those obtained by extending the theoretical model [16,17] by considering the cross-sectional area variation (see Eq. (19) [18]). It is interesting to note that when the acoustic reflection coefficients of inlet and outlet are zero, a positive growth rate is predicted and the premixed laminar flame undergoes periodic motion. A similar finding is made by Silva et al. [19].

These DNS simulations confirm the experimental results obtained from a combustor with a horn connected, as shown in Fig. 1. The experimental and DNS studies provide more insightful physics to understand the intrinsic instability. However, the stability prediction by DNS is not consistent with the theoretical calculation (see Fig. 7 [18]). This is most likely due to the assumptions made in developing the previous model such as neglecting the mean flow and pressure continuity across the flame. These assumptions are not mathematically justified. Neither is consistent with the flow condition in a practical combustor. Generally, a practical combustor is associated with a mean flow [29,30]. Moreover, entropy waves [31,32] may be produced. However, the previous studies ignore the effects of the mean flow, pressure jump and the entropy waves. Lack of these investigations partially motivate the present study.

In this work, a one-dimensional (1D) model of a thermoacoustic combustor with entropy waves and a mean flow present is considered in order to study intrinsic thermoacoustic instability (ITI). To make our analysis more generalized, the cross-sectional area of the combustor is assumed to vary. This is described in Section 2. An entropy-involved energy measure is defined first and an entropy transfer function (ETF) is then derived. The magnitude of the energy measure becomes infinitely large, and the system is unstable, when the magnitude of the entropy transfer function is zero. In Section 2.2, the eigenfrequency, critical gain and growth rate of intrinsic thermoacoustic modes are derived by using the ETF. In Section 3, the present model is used to study intrinsic thermoacoustic instability. Comparison is then made between the present results and the previous ones. Finally in Section 4, case studies are performed to examine the intrinsic thermoacoustic instability based on measured flame transfer and describing functions.

2. Theoretical modelling

2.1. Definition of entropy-involved energy measure

Generally, a practical premixed combustor is associated with different cross-sectional areas upstream and downstream of the acoustically compact flame. Fig. 2 shows the schematics of the modelled combustor in the presence of entropy fluctuations and a mean flow. The cross-sectional areas upstream and downstream are denoted by A_1 and A_2 respectively.

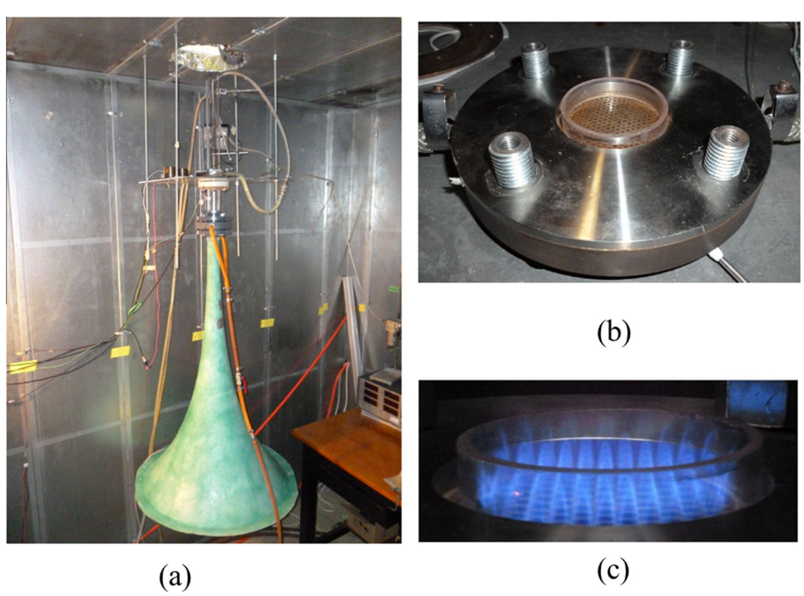

Fig. 1. (a) Experimental setup of the combustor with a horn connected to reduce acoustic reflection, (b) close-up of the burner holder of the combustor, (c) photo of the burner with bunsen type flame anchored [20].