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Response of a conical, laminar premixed flame to low amplitude acoustic forcing – A comparison between experiment and kinematic theories

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This paper presents an experimental study on the dynamics of a ducted, conical, laminar premixed flame subjected to low amplitude acoustic excitation from upstream. The heat release response of the flame to velocity disturbances is investigated through measurement of the so called 'flame transfer function' for a wide range of forcing frequencies. The results are compared with those predicted by the existing linear kinematic theories. It is observed that these theories are in general agreement with the experiment, although there exist some disparities. A detailed comparison of the experimental data with the kinematic theories shows that the phase speed of flame disturbances has an essential influence upon the level of agreement between the theory and experiment. The data-set presented in this work complements that reported in an earlier study. In keeping with others, visualisation of the excited flames clearly shows that the flame response includes waves on the flame front which are formed at the base and then convect along the flame.

1. Introduction

Combustion is expected to dominate power generation and propulsion for the foreseeable future. Intensive research activities are, therefore, being carried out across the world to mitigate the environmental issues associated with the combustion of various fuels [1]. In particular, significant attention has been paid to the reduction of combustion generated air pollutants [2]. To comply with the strict air pollution standards, gas turbines must have minimal NOx emission [2,3]. As a result, the gas turbine industry is moving towards utilisation of lean premixed flames to reduce NOx formation [4]. Lean premixed combustion, although significantly improves NOx emission, is prone to a number of combustor instabilities which include thermoacoustic instabilities [5]. In general, occurrence of these instabilities has hindered the development of lean premixed and pre-vaporised gas turbine combustors [4]. Understanding and suppression of thermoacoustic instabilities are, therefore, an ongoing concern for industry and academia [6,7].

Thermoacoustic instabilities are, usually, the result of a complex coupling between the combustion chamber acoustics and unsteady flame heat release. This leads to the generation of strong pressure waves [7] which, in turn, can result in significant hardware damage, flame blow-out or flashback and loss of control of the system [4]. Importantly, thermoacoustic instabilities may happen in a wide variety of continuous combustion systems including gas turbines, aero-engines, boilers and industrial burners [3]. Consequently, these instabilities are regarded as a major barrier against the wide utilisation of lean premixed, gas turbine combustion [5]. For more than half a century, a substantial amount of effort has been put on understanding, prediction and suppression of thermoacoustic instabilities and the research in this area is ongoing [3]. Yet, there is currently no comprehensive predictive design tool available to identify and eliminate thermoacoustic instabilities at the design stage of combustion systems [4]. As a result, the design of stable combustors relies chiefly on the manufacturer's knowledge and trial and error, which sometimes involves full scale tests [4].

It has been shown by many authors that thermoacoustic instabilities are heavily dependent upon the configuration of the combustion system and, the flame and flow characteristics [5]. In premixed combustors, the most challenging and unknown part of the problem is the response of the premixed flames to acoustic waves [6]. The difficulty, in part, stems from the current lack of a comprehensive understanding on the dynamics of premixed flames [8]. Further, the essential physics of thermoacoustic instabilities are not entirely understood [6,7]. This is mostly due to the complexities

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involved in the interactions between premixed flames and sound waves [9,10] and, to some extent, the effects of system boundaries [11,12].

In practice, it is essential to predict the onset of instability under varying operating conditions. To achieve this, the classical linear stability analysis is, conventionally, conducted through combining the linear flame dynamics with a model of chamber acoustics [6]. This is often regarded as low order modelling and leads to the determination of thermoacoustic stability margins of the systems. In general, low order models are expected to represent the most essential dynamical characteristics of the system, while being simple and easy to use [4]. Detailed understanding of linear flame dynamics is therefore crucial in devising low order flame models and prediction of combustor stability [6]. In recent years, however, it has been demonstrated that thermoacoustic systems can feature strong nonlinear dynamical behaviours [13,14]. These nonlinearities may introduce new stability limits and complicate the stability analysis [15,16].

Laminar flames are often investigated experimentally [17], theoretically [18] and numerically [19,20] to obtain fundamental understanding on the essential physics of flame and sound wave interactions. The resultant physical insight is mostly transferable to more complex cases which include turbulent flames [21]. Experimentally, these analyses are usually performed through exciting a premixed laminar flame by acoustic waves generated by a loud speaker, e.g. Refs. [17,22,23]. Response of the flame is characterised by the velocity modulations just upstream of the flame and the perturbations in the instantaneous flame heat release [17]. In the linear limit, a transfer function is then defined as the ratio of the disturbances in heat release and upstream mixture velocity, respectively normalised by the mean heat release and mixture velocity [5]. This transfer function serves as the dynamic model of the flame in combustor models [6]. It has been also shown that the interaction of acoustic waves with laminar flames can result in further generation of sound [24]. This secondary generation of acoustic waves may, itself, contribute with the thermoacoustic instability of the combustor.

Theoretical investigations of the dynamics of laminar premixed flames usually make use of the 'G equation' [5]. In this approach, the kinematic evolution of the flame front is related to fluctuations of the flame surface area and flame heat release. Fleifil et al. [25] solved the linearised G equation for a laminar flame stabilised in a simple duct flow and developed a theoretical flame transfer function. Later, Ducruix et al. [22] extended this solution to open conical flames. The amplitude of their predicted flame transfer function was in a reasonable agreement with experiment, but the agreement in phase was not as good. This theory was improved by Schuller et al. [23], who assumed convection of flame disturbances along the flame, and obtained better phase agreements with the experiment. The transfer function of Schuller et al. [23] is expressed as.

$$\frac{q'/|q|}{u'/|\overline{u}|} = \frac{2}{St^2}\frac{1}{(1-\cos^2\alpha)} \times \left[1-\exp(jSt)+\frac{\exp\left(jSt\cos^2\alpha\right)-1}{\cos^2\alpha}\right] \tag{1}$$

where $St = (\omega R)/(S_L \cos\alpha)$. Here, the terms q' and $\overline{q}$ are respectively the fluctuating and mean flame heat release (W) and, u' and $\overline{u}$ are the fluctuating and mean velocity immediately upstream of the flame (m/s). Further, St is a Strouhal number and ω, R, S_L, α and j are respectively the forcing frequency (rad/s), flame holder radius (m), the laminar flame speed (m/s), the flame half apex angle and the unit imaginary number ($\sqrt[2]{-1}$). Flame disturbances are the surface waves generated at the flame base which then convect downstream towards the flame tip. Phase speed of the flame disturbance is further defined as the convective velocity of the surface wave. This theory assumes that flame disturbances are convected downstream by the mean, cold flow velocity. Schuller et al. [23] observed some disparities between the theoretical phase response in Eq. (1) and experiment at higher frequencies. This model was later verified experimentally by Karimi et al. [17]. In their experiment a ducted flame was subjected to harmonic downstream travelling acoustic disturbances with varying amplitude and frequency [17]. Karimi et al. found that Schuller's linear theory matched their experimental results generally well [17]. This agreement, however, was limited to low amplitude forcing. At higher forcing amplitudes, the flame response was significantly different to that predicted by Eq. (1) [17]. Karimi et al., further, measured the phase speed of flame disturbances and showed that this quantity varies along the flame and depends upon the forcing frequency [17]. A similar conclusion was made by Birbaud et al. [26,27] in their investigation of free jets and conical flames. Formation of travelling waves on the flames by acoustic forcing has been further confirmed by Kornilov et al. [28,29]. Furthermore, it has been experimentally shown that the presence of an enclosure [30], and also flame anchoring dynamics [31] may affect the flame dynamics.

More recently, the kinematic model of Schuller et al. [23] was extended to non-uniform flow disturbances by Preetham et al. [32]. In this theory the phase speed of the flame disturbances is not necessarily the same as the mean flow speed and can vary freely [32]. Yet, in the theory of Preetham et al. [32] the value of phase speed remains frequency independent and constant along the flame. The resultant flame transfer function is expressed as [32].

$$\frac{\frac{q'}{|\overline{q}|}}{\frac{u'}{|\overline{u}|}} = 2\left(\frac{\eta\left(1-e^{iSt_2}\right)+e^{i\eta St_2}-1}{\eta(1-\eta)St_2^2}\right) \tag{2}$$

where $St_2 = \frac{St}{\alpha} = \frac{St(1+\beta^2)}{\beta^2}$, $\beta = \frac{L_f}{R}$, $\alpha = \frac{\beta^2}{\beta^2+1}$, $\eta = K\alpha$, $K = \frac{u_0}{u_c}$. Further, u_0, u_c, L_f and R are respectively the flow bulk velocity at the flame base (m/s), flame disturbance phase speed (m/s), steady flame length (m) and flame base diameter (m).

The analytical analysis of flame dynamics has been, recently, extended to the time domain by Blumenthal et al. [33]. These authors derived expressions for the temporal response of two different flame configurations subjected to an impulse [33]. Through spectral analysis of their temporal impulse response, Blumenthal et al. [33] restored the previously derived flame transfer functions [23]. In another recent work, Kashinath et al. [34] computed the flame phase speed through direct numerical simulation of an acoustically forced, conical laminar flame. Their results clearly show that the phase speed of flame disturbances varies with the excitation frequency and the location along the flame [34]. Most importantly, they demonstrated that the non-uniformity in flame phase speed can have strong impacts upon the thermoacoustic instability of the combustion system [34]. Most recently, Manoharan and Hemchandra showed that hydrodynamic instabilities could significantly affect the thermoacoustic instability of a step combustor [35]. Through a numerical study, these authors demonstrated that the velocity perturbations caused by hydrodynamic instabilities can perturb the flame heat release and generate thermoacoustic instability [35].

The present survey of literature shows the necessity of including the non-uniformities of flame phase speed into the thermoacoustic low order models. This, in turn, calls for further theoretical development and comparisons between the existing theories and experiments. The present paper aims at responding to this need, through comparing the linear theories of Schuller et al. [23] and Preetham et al. [32] with the experimental results obtained from a