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Impact of the injector size on the transfer functions of premixed laminar conical flames

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ABSTRACT

The transfer function (FTF) of premixed laminar conical flames submitted to flowrate modulations is investigated over a wide variety of injection conditions. The response of methane/air and propane/air flames for cylindrical injectors of radii $R = 11,\ 7$, 1.5 and 1.0 mm is examined. The steady flames investigated all feature the same flame tip half-angle $\alpha = 14.5^o$, i.e., the same aspect ratio $h/R = 4$, where h is the flame height. When the injector radius R is large compared to the flame thickness δ, the FTF measurements are shown to collapse on the same response curve when they are plotted as a function of the reduced frequency $\omega_* = \omega R/(S_L \cos\alpha)$, where ω is the forcing angular frequency and S_L the laminar burning velocity. When the injector size is reduced and δ/R becomes sizable, additional parameters are needed to fully describe the FTF. The Lewis number and flame temperature are shown to alter the low frequency behavior of the FTF of flames stabilized above small injectors. One of the main features of these flames is FTF gain values exceeding unity, called gain overshoots, at low reduced frequencies. Larger FTF gain overshoots are found as the injector size is reduced or as the flame temperature is reduced. A model accounting for mutual flame interactions and unsteady heat and mass transfer at the flame base is derived for the reduced frequency ω_*^0 corresponding to the peak FTF gain values. This expression is shown to better match measurements than previous models based on planar flames that only consider unsteady heat and mass transfer between the flame stand-off position at ψ_0 and the burner. The main finding is that mutual flame interactions due to interpenetrating diffusion layers and unsteady heat transfer at the flame base both lead to FTF gain values exceeding unity but the former mechanism is largely dominant for the configurations investigated in this study. It is finally suggested that the FTF of flames stabilized over small injectors may be fully described by four dimensionless parameters ω_*, α or h/R, ψ_0/R and $\delta \cos\alpha/R$.

1. Introduction

Flame Transfer Functions (FTF) are often used in combination with an acoustic model of the system in order to predict the thermo-acoustic behavior of combustors. This algebraic relation linking heat release rate perturbations to incoming flow disturbances is used to avoid a detailed description of the complex interactions taking place between the flow dynamics, acoustics and unsteady combustion and enables stability analysis of the combustor dynamics at reduced computational costs [1,2]. Due to the major problems caused by combustion instabilities in practical systems, there is a large theoretical, experimental and numerical research effort to develop tools easing the determination of FTF [3–5].

Laminar premixed conical flames submitted to harmonic flowrate modulations constitute an idealized case that can be used to validate theoretical models and numerical simulations [6–8]. It also helps uncover some of the main physical mechanisms controlling the response of premixed flames to incoming flow perturbations [9,10]. Finally, there are many domestic and industrial low power burners operating with premixed conical flames which exhibit regimes with self-sustained combustion oscillations accompanied by large noise emission [11].

It is thus worth developing physics-based models allowing an accurate description of the FTF of premixed laminar conical flames. Much progress was achieved in this field of research and the main findings are summarized in Section 2. However, it will be shown that experimental investigations still remain scarce in particular when assessing (1) the effects of the Lewis number of the mixture that control heat and molecular transport processes in the vicinity of the reaction layer, (2) the effects of thermal dilatation of the

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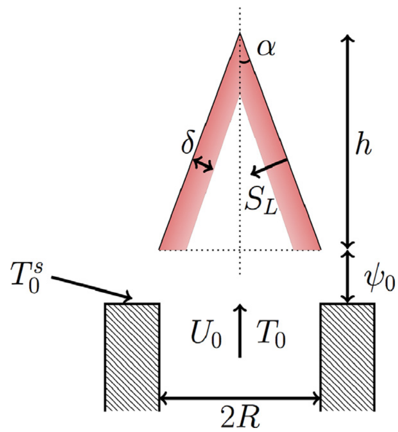

Fig. 1. Simplified structure of a laminar premixed conical flame stabilized above a burner.

burnt gases that act as a feedback on the hydrodynamic velocity field upstream of the flame front and (3) the effects of flame size that modify heat exchange with the burner and change the proportion of fresh gases affected by heat and mass transport near the flame reaction layer.

These three aspects are investigated in this study. The analysis is limited to the response of laminar premixed conical flames submitted to flowrate perturbations in the linear regime. Investigations of the effects of mixture composition inhomogeneities and of the perturbation amplitude may be found in [12,13]. The main observations lead to revisit the physical mechanisms associated with current laminar premixed conical flame FTF models and guide further modeling efforts.

The paper is organized as follows. A review of the current state of knowledge on the physics controlling the FTF shape of premixed laminar conical flames is presented in Section 2. The experimental setup is described in Section 3. The structure of the steady and perturbed flames is analyzed in Section 4. Their FTF is analyzed in Section 5. Section 6 contains a discussion about the experimental results and a new physical interpretation accounting for the experimental FTF is introduced.

2. Transfer functions of premixed conical flames

Let us consider a steady laminar conical flame with a heat release rate $\dot{Q}_0$ stabilized above a burner and fed by fully premixed gases with an injection velocity U_0 as represented in Fig 1. The transfer function of this flame submitted to harmonic flowrate modulations is a linear operator defined in the frequency domain as [9]:

$$F(\omega) = \frac{\dot{Q}_1/\dot{Q}_0}{U_1/U_0} = G(\omega)\exp\left(i\varphi(\omega)\right) \tag{1}$$

where $\dot{Q}_1$ denotes the heat release rate fluctuation around the steady-state value $\dot{Q}_0$ examined at the same angular frequency ω as the incoming harmonic velocity disturbance U_1 around the steady-state injection velocity U_0. Eq. (1) sets a clear framework for theoretical modeling, but already raises difficulties for experiments and simulations.

In practice, the quantity $\dot{Q}_0$ is often taken as the mean value of the unsteady heat release rate signal averaged over many oscillation cycles [9]. In many studies, disturbances of the injection velocity U_1 are also replaced in Eq. (1) by a reference velocity measured at some distance from the burner outlet in a region where the flow is as uniform as possible. The distance between the reference point and flame base needs however to be compact with respect to the acoustic [14] and hydrodynamic [15] perturbations. The forcing level U_1/U_0 needs to be taken as low as possible to avoid nonlinear effects [4,13,16–18], but cannot be set to zero in experiments and simulations. FTF are often made at a fixed perturbation level resulting from a trade-off between maximizing the signal-to-noise ratio and not triggering nonlinear effects. Linearity of the response can be checked by verifying that the measured FTF is independent of perturbation amplitude [13,17]. When this is not feasible, it is better to consider only the Fourier components of the heat release rate and velocity signals at the forcing angular frequency ω and use statistical spectral analysis tools to reduce artefacts due to the finite duration of the signals and the finite sampling rate of the data. In this case, linearity is well approximated if the amplitude of the first harmonic component is at least one order of magnitude lower than the amplitude of the principal component at ω. If all these conditions are met, the simulated or measured FTF converges to the definition in Eq. (1) and corresponds to a complex-valued function that can be expressed as a gain $G(\omega)$ corresponding to the FTF modulus and a phase lag $\varphi(\omega)$ between the response $\dot{Q}_1$ and the input U_1. One of the main advantages of this representation is to explicitly take into account the gain G and phase lag φ dependence on the angular frequency ω.

An extensive research effort has been devoted to finding the main dimensionless numbers controlling the FTF shape of premixed conical flames. The sketch in Fig. 1 represents the main physical and geometrical parameters that are retained in this study, where R is the burner exit radius, U_0 is a reference velocity that does not necessarily correspond to the bulk velocity U_b within the injection tube, T_u is the unburnt gas temperature, T_0^s is the burner temperature, ψ_0 is the stand-off distance of the flame base with respect to the burner outlet, h is the flame height, α is the flame tip half-angle, S_L is the laminar burning velocity and δ is the flame thermal thickness. Additional parameters will be introduced throughout this article.

2.1. FTF of large conical flames

Due to the relative simplicity of the experimental setup, the response of a single laminar premixed conical flame submitted to acoustic forcing has been the topic of many early investigations. These experiments revealed that flame front wrinkling is the main mechanism leading to heat release rate disturbances [19]. Early theoretical analysis aimed at describing the dynamics of these wrinkles and led to simple expressions by analogy with the $n-\tau$ time-lag model from Crocco [20] developed for rocket engines stability analysis. One of the first expressions for the FTF of a premixed conical flame is due to Merk [21]. He found that the FTF phase lag increases with the angular frequency ω and the flame height h and is proportional to the inverse of the injection bulk velocity $\varphi \sim \omega h/U_b$ [21]. However, his model could not capture the behavior of the FTF gain that behaves like a low pass filter.

Progress was made with the introduction of kinematic models based on a G-equation used to analyze the dynamics of flame wrinkles [22]. These models were found to well reproduce the flame front motion observed in experiments by prescribing the correct structure of flow disturbances [22–24]. A linear analysis based on a perturbed G-equation led to the first derivation of an analytical expression for the FTF of elongated conical flames ($\alpha \longrightarrow 0$) in a uniform flow submitted to bulk flow oscillations [25]. Fleifil et al. demonstrated that the FTF was in this case only controlled by a Strouhal number defined as St$=\omega R/S_L$. This model was later generalized to any flame tip half-angle α by introducing the reduced frequency ω_* [9]:

$$\omega_* = \frac{\omega R}{S_L \cos\alpha} \tag{2}$$