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Soot evolution and flame response to acoustic forcing of laminar non-premixed jet flames at varying amplitudes

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ABSTRACT

New details regarding the soot evolution and its controlling parameters in steady and forced flames have been studied using high spatial resolution laser diagnostic techniques. Steady laminar non-premixed ethylene/nitrogen flames with three different diameters burners were acoustically forced using a loudspeaker. 10-Hz-sinusoidal signals of different amplitudes were transmitted to the loudspeaker to drive the flames. The results reveal that the spatial correlation between the soot field and the temperature profile is influenced by the burner diameter and forcing conditions. The soot field in steady laminar flames is confined to a relatively narrow temperature range, 1500–2000 K. In contradiction, the soot field in forced flames spread across a wider range of temperature, 1400–2100 K. Furthermore, the spatial correlation between the normalised soot concentration and primary particle size can be described with an exponential function. While it is observed that the exponential coefficients vary with burner diameter and forcing conditions, further study is necessary for a better understanding. In general, laminar flames forced at a lower amplitude ($\alpha = 25\%$) tend to produce less soot than moderately forced ($\alpha = 50\%$) flames. Further increasing the forcing amplitude to $\alpha = 75\%$ does not increase the soot production in laminar flames; conversely, lower peak and volume-integrated soot volume fraction are observed in the strongly forced flame ($\alpha = 75\%$) as relative to the moderately forced counterpart. These findings shed new light on the seemingly contradictory results published in the literature regarding the effect of the forcing intensity on the soot production.

1. Introduction

There is an ongoing need to increase the understanding of soot evolution in flames. Soot formation and oxidation have practical significance in the development of technologically advanced combustion devices that are highly efficient while producing low emissions, as well as its influences on public health [1–4] and ecology [5,6]. The development of these devices can be accelerated with the aid of robust and predictive soot models. However, despite advanced computational power, the ability to adequately model the complex chemical and physical processes that constitute the soot evolution remains limited [7,8]. To address this issue, systematic experimental data of the parameters controlling soot formation is essential for the development of affordable and accurate soot models. Key scalars that are accessible using non-intrusive techniques include particle size distribution, the volume fraction of soot, along with the governing variables such as temperature and flow field.

Time-varying laminar flames are an intermediate class of flame that bridge the gap between steady laminar and turbulent flames. They exemplify the complex flame–vortex interactions exhibited in turbulent flames. Additionally, due to their cyclic temporal nature, time-varying laminar flames are also particularly valuable as a platform to study flame development and soot evolution in a time-varying flow field. Several experimental [9–15] and numerical studies [16–18] have revolved around time-varying laminar flames. The interest in this subject stems from the fact that time-varying laminar flames provide a broader range of flame conditions than that are available under steady-state conditions. Laser-Induced Incandescence (LII) measurements have shown that acoustically pulsing a laminar steady flame with a frequency of 10 Hz (near to the natural flickering frequency) increases the soot

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production [10]. Furthermore, Shaddix and Smyth [11] reported that while the effect of pulsing on soot enhancement varies with the fuel type (*i.e.*, methane, ethylene and propane), the qualitative intensity of flame flickering has a limited effect on the soot production. However, Connelly [19] provided a contrasting view on the relationship of the soot production with the forcing level via quantifying the modulation of centreline velocity using Particle Image Velocimetry (PIV). While the peak soot concentration increases with the forcing level, the spatial area of the soot field also expands which leads to a substantial rise in the volume-integrated soot volume fraction. Additionally, a numerical study conducted by Kaplan et al. [16] has shown that the peak soot concentration in the forced methane flames increases with the amplitude of the 10-Hz sinusoidal forcing. The study [16] also attributed the augmented soot production under forcing conditions to the lengthening of soot growth residence time in the time-varying flow field as compared to the steady-state. However, Shaddix and Smyth [11] also reported that the peak soot levels measured in ethylene forced flames to decrease as the flame flickering intensity increases, which appears to contradict the trend shown by Connelly [19]. It is worth noting that the burners utilised in [11] and [19] have different diameters, 11.0 and 4.0 mm, respectively and it is unclear how jet diameter affects these processes. A previous study [20] has investigated the soot fields of flames with different diameters to the same forcing conditions, at a frequency of 10 Hz and 50% amplitude (defined as the maximum centreline velocity of forced flames compared to that of steady counterparts). The results show that while the difference in the burner size has an insignificant effect on the peak soot level, it affects the flame structure and hence the spatial distribution of soot. Hence, a larger diameter burner results in a decreased volume-integrated soot volume fraction.

The discrepancy between [11] and [19] motivates the current study to investigate time-varying laminar flames of ethylene in more details. The present study extends the previous measurements in flames with different diameters burners [20] to other forcing amplitudes. The present paper aims to shed new light on the mechanisms that affect the soot evolution in time-varying flames in more details. Furthermore, these measurements for three different burner diameters under both steady and forced conditions constitute a comprehensive database for supporting the development and verification of predictive soot models.

2. Experimental details

2.1. Burner configuration

Figure 1 presents the cross-sectional view of the co-flow burner used in the current study. The burner was designed and built based on the configurations of the Yale Burner [17]. It consists of three interchangeable fuel tubes, with inner diameters of 4.0, 5.6 and 8.0 mm, and a concentric 74-mm-diameter co-flow air passage. A loudspeaker was installed in the plenum below the fuel tube and it was driven by a signal generator to impose a 10 Hz periodic pressure fluctuation on the fuel stream. The frequency of the forcing was chosen to be 10 Hz because it is close to the natural frequencies of all of the three steady laminar flames, and therefore provides the most effective coupling between the flame structure and the flow field [20,21]. The optical diagnostics were phase-locked to the 10 Hz sinusoidal oscillation to acquire phase-resolved measurements.

The fuel stream comprised 41.7% ethylene (C_2H_4) and 58.3% nitrogen (N_2), by volume. The fuel was diluted to limit the maximum amount of soot in the forced flame and thus minimise the level of interference from soot on the laser diagnostic measurements [22]. To isolate the effect of C/O ratio on soot production, the volumetric flow rates of the fuel stream and the co-flow for all the studied cases were kept constant at 0.31 and 60.0 standard litres per minute (SLPM), respectively. All flow rates were measured with mass flow controllers (Alicat Scientific) conditioned to a standard temperature and pressure, 293 K and 1 atm. The normalised amplitude, α, is defined as

$$\alpha = \frac{U_{c,forced} - U_{c,steady}}{U_{c,steady}} \tag{1}$$

where U_c is the centreline velocity and the subscript denotes whether it is for steady or forced flame. Flow conditions for all the flames studied, including the fuel bulk velocity, U_f, and dimensionless parameters (Strouhal, Froude and Reynolds numbers) are given in Table 1.

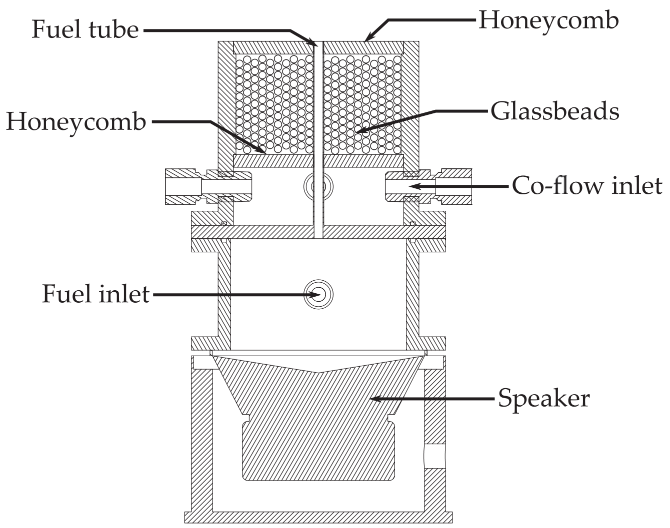

Fig. 1. Cross-sectional diagram of the co-flow burner, which is identical to that of Dworkin et al. [17].

2.2. Temperature measurement

Temperature (T_g) profiles were obtained using the Non-linear excitation regime Two-Line Atomic Fluorescence (NTLAF) technique. The principle of this technique is based on the optical excitation of two neighbouring electronic ground states to a common excited state and the sequential detection of the fluorescence. The flame temperature is then derived from the ratio between the two laser-induced fluorescence signals using an equation described previously [23,24]. The flames were seeded with indium, in the form of complex agglomerates of nano-sized primary particles of indium compounds and spherical micron-sized indium beads, through the fuel stream with an in-house-built ablation device [25,26].

The system-dependent parameters of NTLAF were calibrated in an ethylene/air premixed flame with an equivalence ratio, $\Phi = 2.0$ stabilised on a flat-flame burner. The burner was purpose-designed to produce a matrix of small laminar flames, which subsequently interact and combine to form a stable flat flame of uniform temperature [27]. The flat-flame temperature was measured using an R-type Pt/Pt-Rh 13% thermocouple with a 180-μ m-diameter bead (Omega, P13R-003). A correction of 60 K was added to the thermocouple measurements to account for the radiation heat loss from the thermocouple bead to the surrounding [28]. The phase-averaged images of gas temperature presented in the following sections have a typical signal-to-noise ratio (SNR) of 80:1. The overall uncertainty for the phase-averaged temperature is ±120 K (1σ).