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Influence of nozzle diameter on soot evolution in acoustically forced laminar non-premixed flames

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ABSTRACT

The current study investigated the soot evolution in a series of acoustically forced laminar flames affected by the variations in the nozzle diameter, in-flame residence time and buoyancy. Measurements were performed for three laminar co-flowing non-premixed jet flames in which sinusoidal pressure fluctuations were imposed to the fuel stream. Non-linear excitation regime Two-Line Atomic Fluorescence (NTLAF), Laser-Induced Incandescence (LII), Time-Resolved Laser-Induced Incandescence (TiRe-LII) and Planar Laser-Induced Fluorescence of hydroxyl radicals (OH-PLIF) were performed simultaneously to acquire the phase-resolved measurements of temperature, soot concentration, primary particle size and the location of reaction zones. Additionally, Particle Imaging Velocimetry (PIV) was employed independently to characterise the velocity field. The peak soot concentrations in all the forced flames are double those measured in their steady counterparts, consistent with previous measurements, whereas the maximum particle size for the forced flames is only 10% larger than that for the steady flames and is independent of the nozzle diameter. Nevertheless, a systematic variation of the fuel tube diameter shows that the toroidal vortex scale affects the flame structure which leads to an impact on the spatial distribution and the total volume of soot. In addition, residence time analysis shows that the enhancement of the largest particle size, as well as the peak soot volume fraction, scales with the in-flame residence time.

1. Introduction

Soot occurs naturally in many combustion devices, especially those which employ non-premixed combustion of hydrocarbon fuels. Driven by the desire to develop advanced combustion technologies that are highly efficient and produce low soot emissions, soot formation has been actively studied by the combustion research community for the past half-century [1–3]. Steady laminar flames have always been an attractive system in which to examine the fundamental physical and chemical processes involved in the soot evolution. These flames allow a variety of measurement techniques to be applied consecutively while providing a tractable system in which to examine the soot evolution in spatial and temporal coordinates. Extensive studies on the soot formation processes have established that there is a close coupling between the soot particles, temperature [4,5] and velocity fields [6]. The characteristics of these fields have significant influences on the spatial distribution of the soot, the rates of growth and the oxidation. However, almost all practical combustion systems involve turbulent flows [7]. Turbulent flames are challenging to resolve both experimentally and numerically because the reactions and flow are coupled non-linearly, while the flow and scalar fields fluctuate over time and length scales that span more than eight orders of magnitude. Nevertheless, soot formation in these flames can be characterised by controlling parameters of temperature, stoichiometry, strain rate and residence time [3,8–10]. Numerous studies suggest that turbulent combustion can be viewed as a process dominated by the continuous distortion, extension, production and dissipation of the flame surface by a collection of vortices with a broad range of scales [11,12]. However, complete information on all parameters that control the evolution of soot in a turbulent flame will not be available for many years, owing to the need for simultaneous measurement of them all. In this context, it is desirable to study unsteady laminar flames, which offer the ability to collect more complete data than is possible with turbulent flames and a broader

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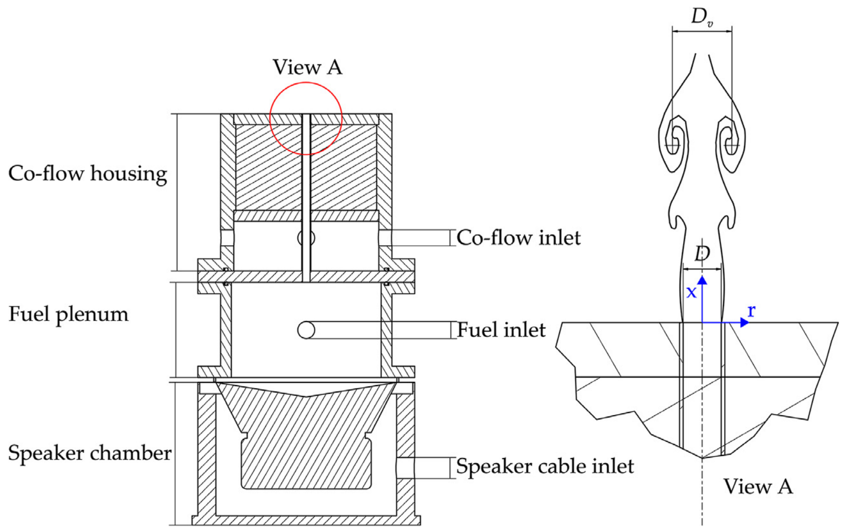

Fig. 1. Schematic representation of the co-flow burner [15], including coordinate orientation and a typical axisymmetric toroidal vortex structure.

range of variation in the controlling parameters than is possible to achieve with steady laminar flames.

In a non-premixed flame, vortices are developed from a modified Kelvin–Helmholtz-type instability [13], which originate within the shear layer between the flame sheet and the cold air. At sufficiently high flow rates, laminar flames exhibit a natural flicker, that occurs at a characteristic frequency but with significant cycle-to-cycle variations. These variations can be kept very low by acoustic forcing at a frequency close to its unforced natural frequency [11]. Acoustically forced non-premixed laminar flames have been extensively utilised to study the effects of time-varying flow field on the soot formation [14–16]. A significant body of work is attributable to Shaddix and co-workers [17–21]. Shaddix et al. [18] reported that the peak soot volume fraction measured in the forced flames can be 2–6 times greater than that of their steady counterpart, depending on the fuel type [18]. A computational study [19] suggests that the increased residence time is the dominant factor that contributes to the enhanced soot production. However, insufficient data are available in these flames to assess quantitatively the performance of soot evolution models, since such assessments also require measurements of temperature, velocity and as many other parameters are possible. The present paper aims to begin to fill this gap.

The natural instability evident in the flickering laminar flames has been studied explicitly using various measurement techniques including fast photography [22], light emission captured by a photodiode [23], and the combination of local temperature and velocity measurements [24]. Sato et al. [25] conducted a dimensional analysis of the flickering frequency, f of laminar flames and found the correlations between the Strouhal number, St, and the Froude number, Fr. The dimensionless numbers are defined by

$$St = f \cdot D/U_f \quad \text{and} \quad Fr = {U_f}^2/D \cdot g \qquad (1)\ \text{and}\ (2)$$

where D is the nozzle diameter, U_f is the jet exit velocity and g is the earth gravitational acceleration, 9.8 m/s^2. The St-Fr relationship obtained at a wide range of experimental conditions could be summarised as $St \propto Fr^n$, where n varies between −0.41 and −0.5. That is, the flickering is almost independent of velocity under some conditions and scales approximately with $\sqrt{D}$. The complex, non-linear nature of this relationship highlights the need for new, systematic data, while the stronger dependence of flicker frequency on D than U_f shows that it is more useful to vary D than U_f.

2. Experimental details

2.1. Burner

The experiment was conducted using a co-annular burner with three interchangeable fuel tubes, having inner diameters of 4.0, 5.6 and 8.0 mm. Figure 1 shows the schematic representation of the co-flow burner along with the coordinate orientation used in the study: other burner details have been described previously [26,27]. The current design is based on the Yale Burner [15]. The fuel tubes were surrounded by a 74-mm-diameter co-flow annulus with dry air running through it. Beneath the fuel plenum, a loudspeaker was driven by a 10 Hz sine wave from a signal generator to impose pressure fluctuations on the fuel stream exciting the central jet. The relatively slow co-flow rolled up into a train of toroidal vortices with a torus diameter, D_v, proportional to the fuel tube diameter. The optical diagnostic systems were synchronised and phase-locked to the sinusoidal waves using a delay generator.

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 to the laser diagnostic measurements [28]. For all the studied cases, the volumetric flow rates of the fuel stream and the co-flow 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 amplitudes of the forcing, α, were defined as the ratio of the maximum centreline velocities, U_c, of the forced flames to their steady counterpart at the exit plane. The corresponding mean exit velocities and other dimensionless parameters for all three different burner jet diameter are shown in Table 1.

A high-speed silicon-based photodetector (DET110, Thorlabs) was used to record the fluctuations of luminosity intensity from the flickering flames. It was placed at a horizontal distance of 300 mm from the flame and at the same level as the mid-height of the flames to capture the dynamic response of the flickering flames. Since every flame has a well-defined characteristic frequency [25,29], the height of the photodetector does not affect the measured frequency. The sampling rate was 1 kHz and for each flame, a total of 23,000 data points were recorded, equivalent to 23 s.