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Experimental investigation of acoustic forcing on temperature, soot volume fraction and primary particle diameter in non-premixed laminar flames

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ABSTRACT

The influence of the acoustic-driven oscillation frequency on the structure and the soot formation of a laminar non-premixed ethylene flame is presented. The flames were forced at either 20 and 40 Hz, corresponding to Strouhal numbers of 0.23 and 0.46. Two-dimensional phase-resolved measurements of gas temperature, soot volume fraction and the diameter of primary particles were measured simultaneously for one steady and two forced flames with non-linear excitation regime Two-Line Atomic Fluorescence, Laser-Induced Incandescence and Time-Resolved LII, respectively. Simultaneous measurements of gas temperature and soot volume fraction provide details of the difference between the flame structure and the soot distribution in the forced and unforced flames. The distinctive features of the forced flames are the occurrence of necking near to the fuel tube and the formation of a hollow soot "shell". Despite the distinctive structure, the soot region is confined to a restricted range of temperatures, approximately 1700–1800 K. The strong spatial correlation between the presence of soot and a narrow range of temperature is well established for steady laminar flames. The present measurements also reveal the complex relationship between diameter of primary particles and soot volume fraction for these flames. Planar gas temperature images and OH* chemiluminescence profiles show that the reaction zone extends periodically upstream from the exit plane of the fuel tube for the flame with $St = 0.23$. This phenomenon, which only occurs for some conditions, is an important consideration for the modelling of these flames because the boundaries of the computational domain typically starts at the fuel flow exit plane.

1. Introduction

The majority of practical combustion devices employ turbulent non-premixed flames to achieve intense mixing and heat release. However, careful design and control is needed to limit the emission of pollutants from turbulent non-premixed flames, such as soot particles, CO and NO_x. With the trend of increasingly stringent limits being imposed on pollutant emissions, there is a growing need for techniques to control the combustion process and achieve low emissions. More reliable predictive numerical design tools are among the techniques needed to enable optimisation of the combustion systems, which in turn requires sufficiently complete and systematic data sets. Furthermore, because of the coupled and non-linear relationships between temperature, strain rate, mixture fraction and soot properties (e.g., volume fraction, aggregate size and diameter of primary particles), simultaneous measurements of these parameters are needed to fully validate models. Unfortunately, practical constraints limit the number of parameters that can be measured simultaneously. While some simultaneous measurements of temperature and soot volume fraction are available [1–3], it will be many years before any one laboratory has sufficient capability to measure all controlling parameters simultaneously. This limitation has restrained the combustion community from performing comprehensive studies of the local instantaneous structure of the reaction zone in unsteady flows. In this context, time-varying laminar flames offer a means to reduce the need for simultaneous measurements by offering an opportunity to examine the local phase-averaged flame characteristics. By using the phase-

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locking techniques, it is possible to independently perform multiple diagnostic techniques at the exact same phase. Furthermore, forced laminar flames exhibit a broader range of flame characteristics than steady laminar flames do.

Time-varying laminar flames typically employ speakers to impose pressure fluctuations on the initial flow profile of fuel jets [4–9]. Other methods to force the fuel flow include mechanical forcing [10,11] and magnetically-induced flow fluctuation [12]. The use of acoustic forcing imposes a periodic oscillation, typically on the fuel flow, which allows different parameters to be measured separately at the same phase and position. In addition, it enables a variety of measurement techniques from different laboratories to be combined. Thus, the need for simultaneous measurements is not as critical. Furthermore, the ability to repeat the measurement at different cycles offers the opportunity to resolve the evolution of a flame through the phase of the cycle without the need for high-speed laser diagnostics. Meanwhile, periodic flows allow the application of phase-average technique to measurements which enhances the signal-to-noise ratio (SNR), thus increasing the accuracy of the measurements. Nevertheless, simultaneous measurements are still desirable to reduce the uncertainties arising from slightly different conditions, such as in phase matching of two distinct data sets. For the above reasons, the present investigation was conducted with simultaneous measurements for one steady and two acoustically forced non-premixed laminar jet flames.

The literature is replete with experimental studies of acoustically forced laminar non-premixed flames [5,6,8,9,13–15] that have been investigated with a variety of diagnostic techniques. From these, two distinct frequency regimes have been identified. One is a low frequency oscillation for which the forcing frequency is close to the natural flickering frequency, which typically range from 10 to 20 Hz [6,14]. The other is a high frequency oscillation, which is typically more than one order of magnitude higher than the natural flickering frequency [8,9,13]. It is well established that the large-scale eddies in jet flames are amplified when the acoustic excitation produces a preferred-mode coupling between jet forcing and the flame structure, which corresponds to a Strouhal number ($St = fD/U_{jet}$) of approximately 0.3. Here, f is the frequency of the forcing, D is the diameter of the jet and U_{jet} is the bulk exit velocity of the jet. When a non-premixed jet flame is excited at the preferred-mode, this leads to a significant increase in the entrainment rate [16] and can result in a reduction in flame length and width relative to its steady counterpart. A reduced flame length and width implies a decrease in the global residence time [17], which typically also reduces the in-flame soot volume fraction. Furthermore, it has been reported that the soot volume fraction decreases when both the flame and the surrounding were forced [8,13]. It has been hypothesised that the acoustic-driven oscillations lead to both enhanced air-fuel mixing and soot suppression [13]. However, strong acoustic excitation at the preferred-mode does not necessarily lead to enhanced mixing and soot suppression. Shaddix et al. [6] and Shaddix and Smyth [7] have reported that the peaks of the soot volume fraction and the size of primary soot particles in forced flames can increase by factors of two to four over their steady counterparts for cases in which the acoustic forcing was driven by a speaker. They concluded that an increase in global residence time is the dominant factor responsible for the measured increase in both the peak soot volume fraction and the diameter of primary particles [18,19]. A recent numerical study of soot evolution in acoustically forced laminar flames has arrived at the same conclusion [20]. The computed soot volume fraction profiles from the previous work [20] were validated against the measurements presented in the current paper. Both the experimental and computational results find that the peak soot volume fraction decreases with an increase in the forcing frequency. In addition, increasing the frequency is also found to reduce the maximum residence time, which is consistent with the decrease in maximum soot volume fraction. Consistent with this, Langman and Nathan [21] reported a case in which forcing of a highly turbulent non-premixed flame at the preferred-mode led to a strong increase in the flame brightness (implying more soot within the flame) but did not generate any measurable change to the global mixing rate. They attributed this apparent contradiction with earlier work to the acoustic forcing in their study being generated entirely naturally (by coupling with a resonance), in contrast to the previous cases in which the acoustic forcing was driven with a speaker, which also added energy to the flow. They concluded that the natural acoustic resonance led to an increase in the residence time of the sooting flow within the large eddies but did not change the overall mixing rate of the flame. Nevertheless, without an in-depth analysis of the local conditions of time-varying flames, together with systematic investigations of a range of conditions, it is difficult to isolate the different effects of alternative non-linear mechanisms that influence flame/vortex interactions.

In light of the incomplete understanding of acoustically forced sooting flames, the present study aims to provide new understanding through measurements of the temporal and spatial profiles in a laminar sooting flame under oscillations forced excitation at several alternative values of Strouhal number. Each flame is investigated using measurements of the gas temperature, the soot volume fraction and the diameter of primary particles. A further objective is to contribute a database for models validation and enhance the predictive capability of these flame models and, in turn, of the evolution of soot in turbulent flames.

2. Experimental details

2.1. Burner

The laminar non-premixed jet flame was generated above a co-flowing burner that replicates a previous design [22,23]. A more detailed description of the burner has been provided by Dworkin et al. [22]. The fuel was introduced through a stainless steel tube with an inner diameter of 4 mm in a concentric 74-mm-diameter co-flow tube. The co-flow was homogenised with two layers of hexagonal honeycomb and 2-mm-diameter glass beads filled in between.

A speaker was placed in a plenum underneath the fuel tube to impose sinusoidal perturbations on the fuel flow. The speaker was driven by a function generator that provided exact reproducibility of the forcing amplitude and phase settings. The optical diagnostics systems presented in Sections 2.3–2.5 were phase-locked to the sinusoidal signal produced by the function generator, permitting phase-specific measurements to be performed in the forced flames. Two frequencies were chosen to force the fuel flow, namely 20 and 40 Hz, corresponding to $St = 0.23$ and 0.46, respectively.

The fuel stream contained a mixture of 32% of ethylene (C_2H_4) diluted with 68% of nitrogen (N_2), by volume. Nitrogen was introduced to limit the maximum amount of soot in the forced flame so that the level of interference from soot to the laser diagnostic measurements was kept to a minimum [24]. The volumetric flow rates of the fuel and co-flow for the steady and unsteady states were 0.264 and 80 litre per minute (LPM), respectively, which resulted in a bulk exit velocity of 0.35 m/s for both the fuel flow and co-flow. The Reynolds number of both jets is 117.

2.2. Velocity measurement

The axial component of the centreline velocity of the non-reacting fuel jet was measured with a Constant Temperature Anemometer (CTA) at a height of ~2 mm above the burner (HAB).