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Impact of acoustic forcing on soot evolution and temperature in ethylene-air flames

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Abstract

This combined numerical and experimental study assesses the transient coupling of soot formation, flame chemistry and fluid transport in ethylene-air coflow flames at acoustic forcing frequencies of 20 and 40 Hz. The measurements report soot volume fraction and flow velocity. For the computational analysis, the numerical code's capability in modeling soot formation is first demonstrated in a steady coflow flame. Soot volume fraction and temperature measurements from different laboratories and optical techniques are used for validation. Then, acoustic forcing is applied to investigate the transient behavior of this multi-dimensional combustion problem. Forcing at different frequencies and amplitudes provokes very distinct transient soot, temperature, and flow conditions. The discussed steady ethylene-air flame is excited with 20 and 40 Hz, corresponding to Strouhal numbers of 0.23 and 0.46. For both frequencies, forcing amplitudes of 20, 50, and 60% are studied numerically and validated against measurements at 50%. With a start-up transient analysis, the computation time to reach a periodic state is evaluated and soot volume fraction predictions are then compared with the measurements. A reduction in maximum soot volume fraction for the increased forcing frequency is observed experimentally and numerically. The decrease in maximum soot volume fraction is explained by a residence time analysis revealing shorter maximum fluid parcel residence times for the 40 Hz than for the 20 Hz case. It is also found that at 40 Hz the transient evolution of maximum soot production and forced fuel velocity is almost synchronized, while for the 20 Hz case, a time lag of 32.5 ms is observed, corresponding to 65% of a full period.

Keywords: Non-premixed flames; Time-varying; Soot evolution; Acoustic forcing

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1. Introduction

A critical assumption in practical combustion systems is the application of chemical models that are typically developed in steady laminar flames. Up to date it is not clear, if the limited combinations of residence times, temperature histories, local stoichiometries, and strain rates sampled in laboratory-scale steady laminar flames are sufficient to quantitatively describe chemical processes in turbulent environments [1].

Non-premixed, oscillating, coflow flames mimic due to the added fluid-dynamical time scales some features of turbulent flows in a simple and well-defined way. Such flames are considered here, to analyze the effect of added flow time scales and to assess the predictive quality of models for these dynamic flows compared in relation to predictions for steady flames. The advantage of this configuration is that it allows transient soot formation studies at a fundamental level, under well-controlled laboratory conditions. Besides, the application of a two-dimensional computational domain makes detailed chemistry simulations with an extended mechanism feasible. At the same time, the flame is complex enough to account for effects such as curvature and variation in residence times by oscillation, which is not the case in simplified one-dimensional configurations that are often used to evaluate soot models [1]. Time-dependent effects are supposed to be of influence due to slow rates of aromatic hydrocarbon formation and soot inception. These formation and inception processes might then decouple from mixture fraction and result in strong sensitivities to flow-field dynamics [2].

Soot suppression or augmentation in acoustically forced combustion processes was investigated by several laboratories over the last decades [2–9]. A recent major combined experimental-computational study on coflow flames was conducted by Dworkin et al. [4] and Connelly [5], where a non-premixed, sooting, ethylene-air flame was diluted with 68% in volume of nitrogen and forced at a frequency of 20 Hz, applying different forcing amplitudes on the fuel flow velocity. It was found that the maximum soot volume fraction increased with fuel flow modulation. A discrepancy in the relative forcing amplitude between the experiments and direct numerical simulation (DNS) was observed. Furthermore, only one sinusoidal perturbation frequency was studied. However, as pointed out by Dworkin et al. [4], a substantial increase in frequency could result in a different flame response, with very different soot characteristics. Sapmaz and Ghenai [10] experimentally studied soot production in forced coflow flames with frequencies ranging from 10 to 200 Hz using a solenoid valve for forcing. They observed an increase in total, volume averaged soot volume fraction when increasing the oscillation frequency. These findings conflict with the ones of Shaddix and Smyth [2] although using a similar burner and flame setup. While in Shaddix and Smyth [2] the integrated soot volume fraction value at 10 Hz equals the steady flame value, in Sapmaz and Ghenai [10] a considerable decrease was found between these two conditions. Shaddix and Smyth [2] also pointed out that some error is inherent in averaging over the limited temporal and axial sampling.

The present study extends the previous combined experimental-computational study [4,5] to 40 Hz. Two acoustic forcing frequencies (20 and 40 Hz) and three different amplitudes (20, 50 and 60%) are computed and validated against measurements at 50% modulation. First the code's capability in predicting soot volume fraction and temperature in a steady coflow flame is assessed followed by analyzing the start-up transient treatment and the prediction of the flame's oscillation frequency. Then, the computationally obtained, transient soot volume fraction fields are compared with the measurements. Experimentally, Laser-Induced Incandescence (LII) has been conducted to measure the in-flame soot volume fraction. The measurements were phase-locked to the flame's oscillation frequency, and ten phases have been assessed throughout each oscillation cycle. Finally, the temporal evolution of the maximum soot production and the temperature is investigated and related to the fuel flow modulation.

2. Experimental configuration and optical diagnostics

A non-premixed diluted ethylene-air flame at atmospheric pressure was established over a coannular axisymmetric coflow burner, identical to the one described by Dworkin et al. [11] and Connelly [5], located at the University of Adelaide. The fuel stream is injected through a 4 mm inner diameter stainless steel tube with a wall thickness of 0.38 mm. It is surrounded by a concentric 74 mm inner diameter air coflow. Both inflows have a bulk velocity of 35 cm/s, corresponding to a Strouhal number of 0.23 for the 20 Hz case and of 0.46 for the 40 Hz case. The fuel and oxidizer flow's Reynolds number is 85 and 1740, respectively. The fuel velocity profile for the studied cases is fully developed, while the air coflow is straightened by two layers of honeycomb sections. The honeycombs have a cell size of 0.8 mm and the sections are separated by glass beads. To avoid saturation of the optical devices during the acoustic flame forcing, ethylene in the fuel stream is substituted by 68% nitrogen in volume. The visible flame length is 23.5 mm, determined by soot luminosity images. The flame length indicates that the flame established in the current study was effectively identical to the flame in previous studies [4,5]. To produce forced, time-varying flames, a loud speaker is located in the fuel plenum. Two–dimensional soot