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Mixture fraction, soot volume fraction, and velocity imaging in the soot-inception region of a turbulent non-premixed jet flame

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Abstract

An experimental study is performed to investigate the feasibility of conducting simultaneous mixture fraction, soot volume fraction and velocity imaging in sooting jet flames. The measurements are performed in the soot-inception region of ethylene jet flames, where the yellow luminous region first appears in the flame. Three-component velocity and soot volume fraction are measured by stereoscopic particle image velocimetry and laser-induced incandescence, respectively. The mixture fraction is inferred from laser-induced fluorescence of krypton gas seeded into the fuel stream. To obtain mixture fraction from the fluorescence signal, the signal must be corrected for density and fluorescence quenching effects. This correction is accomplished by invoking an assumed state relationship that is derived from a laminar strained-flame calculation. Once properly calibrated, the krypton planar laser-induced fluorescence data give the mixture fraction, temperature and major species near the regions of soot formation. The krypton is seeded into the fuel jet at a mole fraction of approximately 4%. The fluorescence of krypton is achieved by two-photon absorption at 214.7 nm and the resulting fluorescence is collected at 760.2 nm. The krypton fluorescence signal is rather weak, particularly near the reaction zones where density is lowest, and so adequate signal-to-noise ratios could be achieved in a region only about 1 mm in height, which effectively limited this study to a line measurement of mixture fraction. The temperature field derived from the mixture fraction field was compared to temperatures obtained from thermocouple measurements. The mean radial temperature profiles using the different techniques show excellent agreement and this serves to validate the methodology used to map from fluorescence signal to mixture fraction and temperature. The resulting data are of high enough quality as to allow the investigation of the kinematics, thermo-chemical state and even the dissipation fields near regions of soot formation.

Keywords: Soot; Turbulent jet flame; LII; PIV; PLIF

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1. Introduction

The prediction of soot emission in practical combustors is complicated by the complex interaction between the turbulent flow, chemical reactions, and soot particle dynamics. Several recent studies have investigated the interaction between soot formation and transport both experimentally (e.g., [1-3]) and numerically (e.g., [4-6]), but there remains a need for more comprehensive measurements of soot together with velocity and quantities that describe the thermochemical state of the flow. For example, simulations indicate that soot formation is related to the local mixture fraction Z and its rate of dissipation χ [7], but such measurements are quite challenging to make in sooting flames and thus have not yet been reported in the literature. Although mixture fraction has not yet been measured in turbulent sooting flames, recent studies have successfully made measurements of temperature and soot volume fraction using simultaneous two-line laser-induced indium fluorescence and laser-induced incandescence (LII) [8]. Furthermore, Burns et al. [9] also reported high accuracy temperature measurements using diode laser excited two-line atomic fluorescence thermometry in low pressure sooting flames. Zhang et al. [10] performed PAH, OH planar laser-induced fluorescence (PLIF) and LII in ethylene and JP-8 piloted jet flames.

To infer Z in sooting non-premixed flames, we apply two-photon krypton PLIF. Two-photon Kr PLIF is a relatively new technique that has proven useful for making Z measurements in Sandia target flames [11]. Kr is a noble gas and is chemically inert in the presence of combustion, and thus its concentration can be related to Z provided a suitable state relationship is available to account for density and fluorescence quenching effects. In more recent work, the suitability of Kr PLIF to make Z measurements in sooting flames was investigated. In Ref. [3], a preliminary study was conducted where Kr PLIF was applied in the soot inception region of non-premixed ethylene flames. Kr was seeded into the ethylene (C_2H_4) jet at mole fractions of 4% and 8%, and it was shown that PLIF signal profiles 10 diameters downstream remained undistorted by absorption or stimulated emission effects for the 4% case [3]. It was demonstrated that the Kr PLIF technique holds promise for making Z measurements even in sooting flames; however, it remained only qualitative since quenching corrections were not made to the Kr fluorescence signals.

The present study seeks to experimentally quantify Z and soot-volume fraction (f_v) fields, and kinematics in the near-field soot-inception region of a jet flame using simultaneous diagnostics including two-photon Kr PLIF, stereoscopic particle image velocimetry (sPIV) and LII. The flame of interest is a turbulent, non-premixed $C_2H_4/N_2/Kr$ jet flame at a jet Reynolds number of 8300. From these measurements simultaneous planar fields of mixture fraction, temperature, three-component velocity and soot volume fraction are measured in the soot inception region to provide new information on the formation and transport of soot in a turbulent flame.

2. Experimental approach

Experiments were performed in a turbulent non-premixed jet flame that was surrounded by a co-flow of air. The co-flow was generated using a nozzle with a contraction area ratio of 2.8:1, and which had a $36 \times 36\ cm^2$ exit area and a length of 76.2 cm. The co-flow velocity U_{co} was 0.7 m/s. The length of the jet delivery tube was 130 cm and the jet nozzle diameter, d was 1 cm. The bulk jet velocity was about 12.5 m/s. The Reynolds number at the jet flow exit was 8300. The fuel mixture consists of 50% C_2H_4, 46% N_2, and 4% Kr by volume, giving a stoichiometric mixture fraction, $Z_{st} = 0.128$. The addition of 4% Kr (by volume) was introduced in the fuel jet stream as the tracer for the PLIF measurements.

This study follows the approach of Hsu et al. [11] and the preliminary study of Ref. [3]. The fluorescence of Kr is achieved by exciting the ground state ($4p^{6}\,{}^1S_0$) to the $5p[3/2]_2$ state transition, a transition accessible via two-photon absorption at 214.7 nm [12]. The resulting fluorescence is collected at 760.2 nm, arising from the decay of this upper state to the $5s[3/2]_2$ state [12]. The natural lifetime of this fluorescence is 26.4 ± 0.5 ns [13]. The 214.7 nm beam was produced by sum frequency generation method. The third harmonic (355 nm) of a Nd:YAG laser and output of a dye laser (544 nm) were combined in a Type I BBO crystal.

The 214.7 nm laser beam (2 mJ/pulse) was focused with a 500 mm fused silica cylindrical lens into a small sheet of height 4 mm and thickness 250 μm. The small sheet height was used to maintain high laser intensity since the two-photon signal scales as intensity squared. The fluorescence was imaged through a 760 nm bandpass filter (10 nm bandpass) to reject unwanted radiation. The intensified camera was gated to 50 ns. Note that the signal-to-noise ratio (SNR) is only sufficient over a small region near the peak of the laser sheet because the Kr PLIF signal is nonlinear; therefore, the data shown here were restricted to a height of only 1 mm.

Both the fuel-jet and coflow were seeded with aluminum oxide (Al_2O_3) particles of nominal diameter 0.5–1.0 μm for PIV. The Δt between the two PIV pulses was set to 32.5 μs. Two 2048×2048 pixels CCD cameras were used in a stereoscopic alignment to capture the 3-component PIV images. The cameras were fitted with 105 mm focal length lenses mounted to Scheimpflug mounts. Both PIV cam-