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Simultaneous planar measurements of temperature and soot volume fraction in a turbulent non-premixed jet flame

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Abstract

New measurements are reported of the soot–temperature interaction in a turbulent non-premixed ethylene–hydrogen–nitrogen attached jet flame with an exit Reynolds number of 15,000. Spatially resolved, two-dimensional temperature and soot volume fractions were measured simultaneously using non-linear excitation regime two-line atomic fluorescence (NTLAF) and laser-induced incandescence (LII) techniques, respectively. The soot–temperature correlation is presented and analyzed through representative images of single-shot simultaneous temperature and soot volume fraction at various heights, as well as through joint probability density functions (PDFs) of soot volume fraction (*SVF*) and temperature. A strong influence of temperature on *SVF* is found, which is consistent with current understanding of their inter-dependence. Axial and radial plots of mean *SVF* categorized into temperature bands of 300 K are also reported. These reveal that, while the mean *SVF* is a function of both temperature and axial distance, the joint PDF depends only weakly on radial distance. The study highlights the value of the simultaneous measurements for understanding soot behavior in a turbulent environment and for model development and validation.

Keywords: Temperature; Soot; Simultaneous; Non-linear two-line atomic fluorescence; Laser-induced incandescence

1. Introduction

The processes of soot formation, growth, and oxidation in practical environments are highly complex, as they are correlated with interdependent and coupled parameters such as temperature, pressure, mixture fraction and strain rate [1]. The relationship between soot concentration and temperature is one of these that are of crucial importance to the understanding of soot behavior in a flame. Temperature and soot have an intrinsic coupled dependence, since temperature influences soot formation and destruction processes in a flame, while depending in turn on soot

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concentration due to heat transfer through incandescent radiation from soot particles [2,3]. For this reason, the development of both a thorough understanding and predictive models of soot evolution in a turbulent flame requires the simultaneous measurement of temperature and soot concentration.

The attempt to assess the soot–temperature interaction in a turbulent environment has been reported previously via different techniques. Chan *et al.* [4] reported simultaneous measurements of temperature and soot concentration in premixed and non-premixed flames; however, these measurements were performed in laminar and wrinkled flames only [4]. Sivathanu *et al.* [5] reported simultaneous measurements of temperature and soot in low turbulence diffusion flames and in the fuel-rich region only, using an optical probe and a two-wavelength pyrometry technique for measuring soot concentration and temperature, respectively. Köhler *et al.* [6] reported measurements of average temperature, using shifted vibrational coherent anti-Stokes Raman spectroscopy (SV-CARS), along with simultaneous measurements of soot volume fraction and flow velocity in a lifted turbulent jet flame. However, despite their significance [5,6], the temperature measurements in these studies were performed using single-point measurement techniques. The three-dimensional and unsteady nature of turbulent flames makes it highly desirable to provide measurements in multiple dimensions, allowing the acquisition of spatially correlated scalars and their gradients which influence soot evolution [7]. Finally, to allow the joint application of experiments and computational fluid dynamics, (CFD) model development, from which the major advances in combustion research have been derived, it is necessary for the experiments to be performed under very well characterized conditions. In a similar vein, owing to the complexity of soot evolution in turbulent flames, it is desirable that measurements be performed in attached turbulent flames, since lifted flames are not only more difficult to predict but also strongly inhibit soot formation through partial premixing [8,9]. Importantly, no simultaneous measurements of temperature and soot concentration in a well characterized and attached turbulent jet flame have been reported previously, while no simultaneous planar measurements of these parameters in a turbulent sooting flame are available at all. Hence the aim of this investigation is to meet this need.

Non-linear excitation regime two-line atomic fluorescence (NTLAF) has recently emerged as a technique that can be applied to provide planar single-shot temperature imaging [10]. The NTLAF technique, which is an extension of Two-line Atomic Fluorescence (TLAF) thermometry into the non-linear excitation regime, involves seeding a metal tracer into the flame, of which indium is the preferred species owing to its good sensitivity over the temperature range 800–2800 K [11,12]. The application of NTLAF in turbulent flames has been demonstrated by Medwell *et al.* [13] where temperature measurements obtained with NTLAF have been found to generally agree with a well characterized turbulent non-premixed flame, known as the TNF DLR-A flame, to within approximately 100 K. Both NTLAF and Laser Induced Incandescence (LII) have been applied simultaneously in laminar flows, and no significant interference of the two measurements on each other was observed [4]. For these reasons, NTLAF and LII were chosen for the simultaneous measurement of temperature and soot concentration in this study.

Soot–turbulence interactions in turbulent flames have been the subject of several recent studies. Qamar *et al.* [14] investigated the soot formation and growth in turbulent flames. They demonstrated that the instantaneous single-shot images give a more comprehensive picture of soot formation than the averaged data and are likely necessary to fully understand how soot affects combustion devices. Similar observations were made by Köhler *et al.* [6] who demonstrated that the unconditional mean soot volume fraction is a function of both the radial and axial locations of the flame. Lee *et al.* [15] evaluated mean *SVF* taking intermittency into account. They reported that the radial profile of the intermittency index is a strong function of axial location, as expected. Similarly, the average soot volume fractions vary significantly with both axial and radial positions. These measurements [6,14,15], despite their importance, provide little to no information about the joint dependence of soot on the instantaneous local temperature field, radially or axially.

For the reasons described above, the aim of the present investigation is to provide new insight into the evolution of soot in a well characterized, attached turbulent jet flame through a statistical assessment of simultaneous measurement of planar temperature and soot volume fraction, while also supporting model development and validation through new joint statistics.

2. Experimental

2.1. Burner details

The burner comprises a round aluminum tube of 4.4 mm ID, through which fuel is supplied at a velocity of 57 m/s with a bulk exit Reynolds number of 15,000 and a volumetric composition of 40% C_2H_4, 40% H_2, and 20% N_2. The pipe is mounted in the center of a contraction delivering co-flowing air at ambient temperature and at a mean velocity of 1.1 m/s. The contraction has a square cross-section of dimensions 150 mm by