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Simultaneous imaging of temperature and soot volume fraction

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Abstract

This paper demonstrates the first *simultaneous* single-shot imaging of temperature and soot volume fraction, measured with nonlinear regime two-line atomic fluorescence (NTLAF) and laser-induced incandescence (LII), respectively. The measurements are performed in laminar premixed and nonpremixed flames, and in a wrinkled nonpremixed flame. No significant interference of the two measurements on each other is observed. This study demonstrates a major advance in the capacity to assess the interdependence of temperature and soot in flames of practical significance.

Keywords: Temperature; Soot; Two-line atomic fluorescence; Laser-induced incandescence; Simultaneous

1. Introduction

Soot is one of the key components in many combustion systems. Soot, when present within a flame, plays an important role in radiative heat transfer — the dominant heat transfer mode in kilns, boilers and furnaces [1,2]. An increased presence of soot within a flame acts to increase the flame emissivity and hence the radiative heat output. This is because soot produces broadband incandescent radiation, which typically dominates over the narrow-band radiation from intermolecular processes. The presence of soot within practical combustion systems is important because it tends to increase with physical scale, owing to the accompanying increase in residence time and reduction in strain rates. Beyond a flame, unburned soot can either be emitted as an air pollutant, or as a source of "carbon black" as feedstock for manufacturing, depending on the application [3]. While combustion processes involving soot have been widely employed for many years, the processes of its formation and destruction in practical environments are beyond present capacity to understand adequately [4]. These complex processes are governed by interdependent parameters such as fuel type, mixture fraction and temperature [5]. At the same time, many of these dependencies are coupled in the presence of turbulence. Of the various coupled dependencies, soot concentration and temperature remain crucial to the understanding of soot [6].

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Soot concentration distribution measurements within a flame provide valuable insights to the study of soot growth and radiant transport [7,8]. Temperature, on the other hand, characterizes the heat transfer process and controls the chemical and physical processes within a flame [9]. Soot and temperature have an inherent coupled dependence since temperature depends on soot concentration due to heat transfer through radiation. At the same time, the temperature affects the formation and destruction of soot in flame [10]. Therefore, a detailed understanding of soot requires the knowledge of temperature and vice versa. It is well-known that simultaneous measurements of multiple parameters is highly desirable to give the most useful description of a flame [11,12]. In a turbulent environment, it is also highly desirable for the measurements to involve more than one dimension, permitting the acquisition of spatially correlated measurements and the measurements of gradient, which are useful in research and in the study of practical combustion systems [11]. It is for this reason that detailed *simultaneous planar* measurements of soot concentration and temperature within a flame environment are essential to shed light on the complex processes associated with soot.

Laser diagnostics measurements are typically suited to provide simultaneous, multi-dimensional measurements that are well resolved [13]. Their application in flames containing soot has been problematic, however [14]. Absorption, scatter, and other interferences due to the presence of soot and its precursors prevent many established laser diagnostic techniques from being applied reliably to such flames. Several approaches, such as Filtered Rayleigh Scattering (FRS) [15,16] and Coherent Anti-Stokes Raman Spectroscopy (CARS) [6,16–18], have been explored for measurements in sooting flames. FRS is susceptible to variation in the Rayleigh cross-section across the reaction zone, further complicated by the requirement for the knowledge of the spectral broadening behaviour. These variables are difficult to account for, especially in turbulent nonpremixed imaging applications [19]. CARS, on the other hand, is limited by the necessity for line-of-sight optical access, the experimental complexity, and the lack of spatial fidelity (typically of the order of millimetres) in comparison to planar techniques [13]. However, the restriction of the CARS technique to a single point measurement remains the main limitation. Alternative techniques to FRS and CARS have also been developed that may offer measurements in sooting environments [20–22], but remain immature. There is therefore a need for other planar imaging methods of temperature in the presence of soot.

Perhaps the most promising alternative to facilitate temperature imaging in a sooting environment is two-line atomic fluorescence (TLAF), using indium as the seeded atomic species [23–25]. The inelastic nature of the TLAF technique enables optical filtering to minimize interferences from spurious scattering, allowing measurements to be performed in particle-laden environments, notably containing soot [26,27]. TLAF offers two-dimensional measurements, with the added benefits of good sensitivity within a temperature range relevant to combustion and insensitivity to collisional quenching effects [28]. Significant breakthrough in the capabilities of TLAF to provide single-shot imaging was provided by the authors [29] who extended the technique into the nonlinear excitation regime. Nonlinear regime two-line atomic fluorescence (NTLAF) was shown to provide superior signal and improve on single-shot precision (determined by inter-pixel noise) in premixed flames from ~250 K for conventional TLAF to ~100 K. However, previous investigations have mostly been limited to laminar premixed environments.

The aim of this paper is to assess the technical feasibility of conducting *simultaneous* single-shot temperature imaging using NTLAF and soot volume fraction measurements with the laser-induced incandescence (LII) technique [30]. These measurement techniques are selected with a view towards future application in turbulent environments as they offer the advantage of planar imaging. The concurrent application of the NTLAF and LII techniques has the potential to result in interference and it is therefore necessary to demonstrate that simultaneous imaging with these two mehods is possible. This paper also aims to measure and evaluate the fluorescence, temperature and soot volume fraction single-shot images. A laminar premixed, a laminar nonpremixed and a wrinkled nonpremixed flame are chosen to provide flame mediums with distinct features to be used for these assessments.

2. Experimental

2.1. Burner details

The burner used in this study consists of a circular ceramic honeycomb matrix (∅ 80 mm) of $1 \times 1\ mm^2$ pores with ~0.25 mm wall thickness. The honeycomb matrix is encased in a brass annular tube of 80 mm ID. A second annular tube of 100 mm ID is aligned to provide co-annular flow. This burner is used for calibration and to stabilise the premixed and nonpremixed flames examined in this paper. When operated in premixed mode the flame is shrouded by a nitrogen coflow. In the nonpremixed mode no coflow was introduced. To prevent buoyancy-driven instability, a stabilisation plate (∅ 100 mm) is mounted 30 mm above the burner face. The fuel used throughout this paper is industrial grade ethylene ($> 99.5\%\ C_2H_4$).