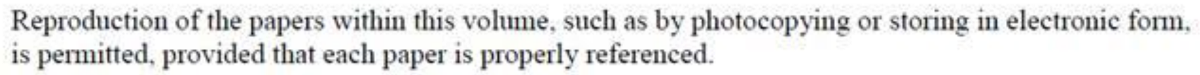
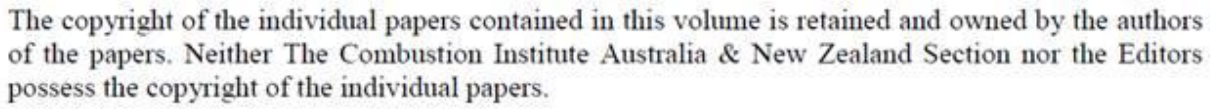
Medwell, Paul Ross; Pham, Phuong X.; Masri, Assaad Racid Temperature measurements in a turbulent spray flame using NTLAF Proceedings of the Australian Combustion Symposium, Perth, WA, 6-8 November 2013 / Mingming Zhu, Yu Ma, Yun Yu, Hari Vuthaluru, Zhezi Zhang and Dongke Zhang (eds.): pp.279-282





http://hdl.handle.net/2440/82568

Proceedings of the Australian Combustion Symposium
November 6-8, 2013, The University of Western Australia

Temperature Measurements in a Turbulent Spray Flame Using NTLAF

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Abstract

This paper reports the first measurements of temperature in turbulent dilute spray flames of acetone using non-linear excitation regime two-line atomic fluorescence (NTLAF), a technique well suited for temperature measurements in flames laden with particles and droplets. The NTLAF technique has previously been successful at measuring temperature in turbulent non-premixed flames of gaseous fuels in the presence of soot. Temperature is extracted from the fluorescence ratio collected of two lines of indium generated from indium chloride which is seeded into the flow. The non-linear excitation regime is exploited to improve the signal-to-noise ratio of the measurements. In the current arrangement, indium chloride is seeded with the acetone fuel and laminar premixed flames of methane are used for calibration. The preliminary results are promising and indicate that the presence of droplets does not affect the signal, making NTLAF particularly well-suited to measure temperature in turbulent, dilute spray flames.

Keywords: Non-linear excitation regime TLAF, Thermometry, Spray flames, Turbulent combustion

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1. Introduction

Spray combustion is important in transport and industrial applications as well as power generation where typically dense, transient liquid spray jets are injected as fuels. Measurements in such flows are extremely difficult due to the presence of dense liquid filaments, droplets and soot. Statistically stationary, dilute spray flames are seen as an important class of flows with manageable complexity yet relevant for the development of fundamental understanding of spray combustion [1]. Well-characterised, dilute spray burners enable the application of laser-based measurements in well-characterised flames for the purposes of model validation [2]. A review of dilute spray combustion, with a particular focus on modelling of these flames, is provided by Jenny *et al.* [1].

Renewed interest in clean alternative fuels and recent advances in laser diagnostics has enabled the development of new capabilities to probe dilute spray flames. For example, laser-induced fluorescence (LIF) imaging of selected species in-situ within a flame, such as OH, CH_2O, or fuel vapour has been applied along with Mie scattering from the fuel droplets [1,3]. More recently, high-speed OH-LIF imaging has been used to reveal the evolution of the reaction zone [4] in turbulent spray flames. However, measurements of critical parameters such as mixture fraction and temperature in spray flames remain elusive [5]. This paper addresses one of these problems and introduces an approach to measure temperature in dilute spray flames.

The two-line atomic fluorescence (TLAF) technique has been demonstrated as a viable approach to collect temperature measurements in flames containing soot. The operating principle of TLAF is the sequential excitation from two lower energy states of an atomic species, typically indium. The resultant fluorescence is detected at the opposite wavelength of the excitation process. For convenience these transitions are referred to as Stokes (410nm excitation, 450nm detection) and anti-Stokes (450nm excitation, 410nm detection). The extension of TLAF to the non-linear excitation regime, so called NTLAF [6], has enabled instantaneous temperature imaging in turbulent non-premixed gaseous flames [7] and flames containing soot [8]. In turbulent non-premixed flames the NTLAF technique has been shown to have an accuracy of approximately 100 K [7].

Two alternative seeding arrangements have been considered for NTLAF; nebulisation of a solvent containing indium chloride, and laser ablation of a solid indium rod [7]. A range of solvents were considered for the nebulisation seeding approach [9], however, for gaseous flames they all introduce physical changes compared with the non-seeded flame. The laser ablation technique eliminates many of these issues, but introduces new complexities which are yet to be fully resolved [10,11]. In the case of spray flames, there is an opportunity to seed the fuel with indium chloride and thus avoid the need for introducing an additional stream into the flame. Although the NTLAF technique has been reported to be immune from interferences due to scattering from soot, it is unclear whether interference from the fuel droplets in a spray flame will allow the seeding advantages of this flame type to be realised. The aim of the current paper is, therefore, to assess the feasibility of conducting instantaneous single-shot temperature imaging in turbulent spray flames using the NTLAF technique. A series of pilot-stabilised, turbulent flames of acetone fuel are used as a measuring platform.

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2. Experimental Setup

2.1 Burner Details

The piloted burner design adopted in this study has been used previously to develop an understanding of auto-ignition [2] and combustion [3,12] in turbulent, dilute sprays. Figure 1 shows a sectional view of the burner which has a simplified design and well-controlled boundary conditions to facilitate modelling. The spray is formed upstream of the jet exit plane by an ultrasonic nebuliser (Sonotek). With the use of air as a carrier gas a turbulent jet issues from the central pipe (D=7mm, 196mm long). Acetone is selected as the fuel, which in this burner configuration, has an advantage over heavier fuels due to its simpler chemistry, higher level of evaporation and a reduction in the amount of droplet shedding. The use of acetone and an ultrasonic nebuliser reduces the amount of complex droplet structures and coagulation encountered with air-blast atomization [3,13]. Details of four selected target flames are presented in Table 1. The spray flame is stabilised by a pilot flame surrounding the central fuel jet. The carbon/hydrogen atomic ratio of the stoichiometric acetylene/hydrogen/air flame is chosen to match that of the liquid fuel (acetone).

For the purposes of the NTLAF technique, indium chloride is added to the acetone fuel supply at a concentration of 375 mg/L. The seeding density of indium chloride is arbitrary and is selected here to provide a good LIF signal without excessive use of seed. All fuels and gas supplies are controlled with appropriate flowmeters.

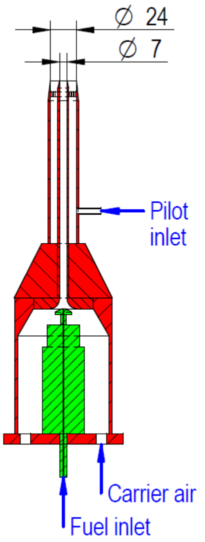

Figure 1: Dilute spray burner

Table 1: Acetone target jet flame conditions

Flame	Fuel flowrate (g/min)	Air flowate (g/min)	Re_{jet}
A1	13	100	16,500
A2	13	125	25,000
A3	9.5	100	16,500
A4	9.5	125	25,000

2.2 Optical Arrangement

The details of the NTLAF experimental layout have been outlined in previous publications [6,7]. In brief, two Nd:YAG-pumped dye lasers are fired with 100ns separation, to produce the required 410nm and 450nm excitation beams. The two 2mJ/pulse beams are combined and directed through a cylindrical telescope lens system to produce a coplanar sheet of 300 µm thickness. The beams are directed through two glass slides. These scattered beams are imaged with a CCD camera to provide shot-to-shot corrections of spatial variations in the laser energy profile across the sheet height.

The burner is translated vertically to perform measurements at different axial locations in the flame. The frequency-shifted indium fluorescence signals are subsequently detected through interference band-pass filters (410nm and 450nm) using two gated intensified CCD (ICCD) cameras. The gate width of the intensifier is set to 50 ns. This filtering rejects flame emission and elastic scattering from droplets within the flame. The resultant images are spatially matched with sub-pixel accuracy.

Determination of the temperature from the indium fluorescence images with the NTLAF theory requires three calibration constants to be ascertained. This process involves performing measurements in a series of well-characterised laminar premixed flame conditions with a flat-flame burner mounted in the probe volume before and after the turbulent spray flame measurements. The premixed calibration flames are natural gas / air across a range of different equivalence ratios, thus giving an environment of controlled temperature and composition. Indium chloride is seeded to the air stream of the premixed flame with an ultrasonic nebuliser. For each calibration flame the temperature is determined from radiation-corrected thermocouple measurements; an approach that has been previously validated [6]. The indium fluorescence (both Stokes and anti-Stokes) is plotted as a function of the laser energy, which is varied with the addition of a set of different neutral-density filters to the beam path after the cylindrical telescope but before the measurement volume. This process enables the curve-fitting constants to be determined which relate the non-linear behaviour of indium fluorescence as a function of laser energy. These constants are required in the NTLAF equation [6] which is subsequently used for the turbulent flames. The process of using a different fuel and flame type for the calibration and the measurements is well-established with this technique [6,7,14].

3. Results

3.1 Flame Appearance

Figure 2 shows photographs of the target acetone flames which, as shown in Table 1, have different liquid fuel flowrates (Cases A1 and A2 compared with A3 and A4) or different carrier flowrates (Cases A1 and A3 compared with A2 and A4). Given the same liquid loading, flames A2 and A4 are closer to blow-off, and slightly shorter than their counterparts (flames A1 and A3, respectively), due to the higher jet Reynolds number. Flame A4 is closest to blow-off and hence the shortest flame as shown from the images of Fig. 2. However, all four flames remain attached to the jet exit plane due to the existence of the pilot. The flames are also clean of soot and do not feature droplet shedding from the burner's exit plane. The three measurement locations (x/D = 5, 10 & 20) are also indicated in Fig. 2.

3.2 Instantaneous Fluorescence Images

To demonstrate the efficacy of the liquid-fuelled seeding approach, Fig. 3 shows a series of instantaneous indium fluorescence images for target flame A1 at the three measurement locations. Each image window shows simultaneous Stokes and anti-Stokes indium fluorescence, respectively, on either side of the jet centreline (where the anti-Stokes image has been flipped left–right). Images at different heights are uncorrelated in time, but a constant colour-scaling throughout all images is adopted.

Figure 3 indicates that indium fluorescence is achieved at all measurement locations. Consistent with previous studies where indium is introduced as indium chloride, fluorescence signal is not detected in the potential core of the jet because the indium salt must interact with the reaction zone to release neutral indium atoms [14]. Nonetheless, strong signal is achieved across the region of interest, namely the reaction zone. Importantly, the images show no evidence of interference. This was further confirmed by de-tuning the dye laser wavelength away from the indium excitation transitions.

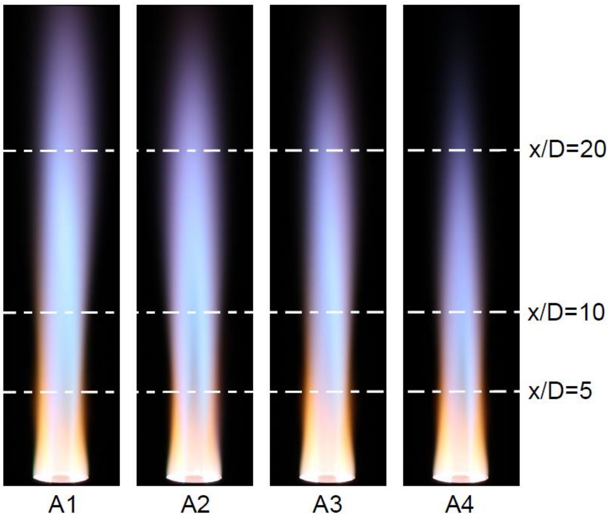

Figure 2: Photographs of the four target flames (Table 1). Image height=200mm.

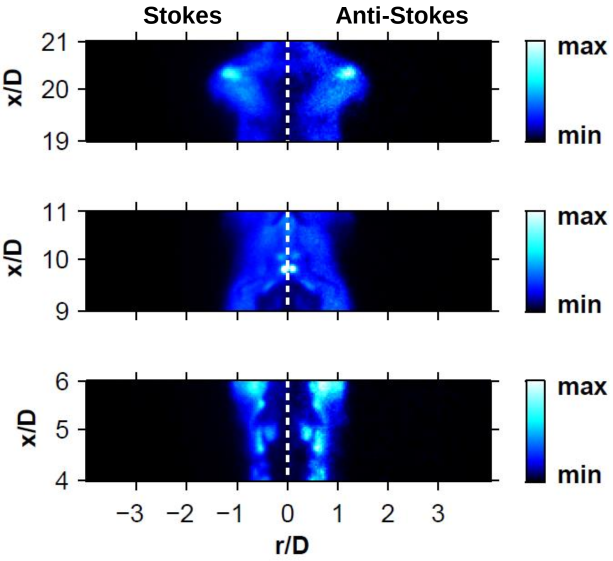

Figure 3: Selection of instantaneous indium fluorescence images for target flame A1 at various x/D locations. Images at each x/D are time independent, but have a constant colour-scale.

The signal-to-noise ratio (SNR) of the instantaneous fluorescence images is ~20:1 for Stokes and ~10:1 for anti-Stokes. These results are an improvement over previous gaseous turbulent jet flame measurements using the NTLAF technique [7].

To compare the fluorescence signal level throughout the length of the four target flames, Fig. 4 presents total Stokes fluorescence yield from 200 images at each measurement location. The total fluorescence for each flame is normalised relative to the x/D=5 location. Figure 4 indicates that the conversion process of indium chloride to neutral indium atoms continues throughout the flames. At x/D=10 the indium has had sufficient opportunity for the indium chloride to interact with the flame front to release the neutral indium atoms. By x/D=20 there has been extensive dilution of the fuel stream due to mixing with the air, and the indium is believed to react with the surrounding oxygen [9] and thus reduces the fluorescence yield.

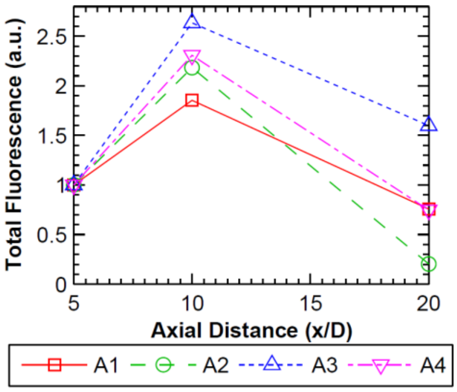

Figure 4: Total Stokes indium fluorescence yield at each x/D location for the four target flames (Table 1). Each flame normalised to the x/D=5 location.

3.3 Instantaneous Temperature Images

Figure 5 shows a selection of instantaneous temperature images at various axial locations in flame A1. The interpixel "noise" is improved compared with previous seeding approaches [7], which is now 130K (6%) in the deduced instantaneous temperature images. The lower temperature limit imposed in the image processing for the NTLAF technique is ~800 K. Previous studies in turbulent flames [7] have required a higher temperature threshold, corresponding to 1200 K, to reduce noise issues associated with the low anti-Stokes signal below this temperature.

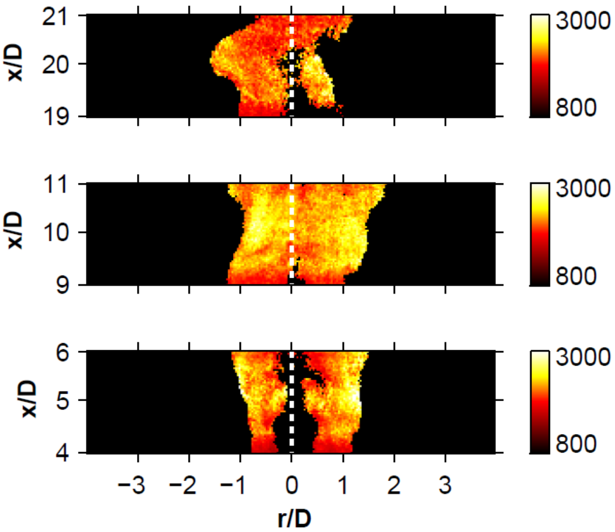

Figure 5: Selection of instantaneous temperature images for target flame A1 at various x/D locations. Images at each x/D are time independent, and all images have the same constant colour-scale (in Kelvin).

It should be noted that, consistent with previous NTLAF measurements, temperature data is only available above a certain temperature limit and is favoured under fuel-rich conditions. The conditional nature of the measurements, therefore, requires care with analysis and interpretation. Nonetheless, the temperature images presented indicate the effectiveness of the NTLAF technique in these dilute turbulent spray flames.

4. Conclusions

Non-linear excitation regime two-line atomic fluorescence (NTLAF) has been successfully applied to a set of turbulent dilute spray flames of acetone. The fluorescence signal is found to be immune to scattering/interference from the spray droplets and vapour. The liquid-fuel spray flames have been demonstrated to be highly effective for seeding indium (required for NTLAF). The dilute spray burner is ideally suited to NTLAF thermometry with potential for additional simultaneous measurements via other laser diagnostic techniques.

5. Acknowledgments

The authors are grateful for the support from the Centre for Energy Technology (CET) and The University of Adelaide. Contributions to the development of the NTLAF technique by Graham "Gus" Nathan, Bassam Dally, Zeyad Alwahabi, Qing Nian "Shaun" Chan, and Saleh Mahmoud are greatly appreciated. Agisilaos Kourmatzis and Nakul Prasad contributed useful discussions with the burner operation. The Australian Research Council (ARC) is acknowledged for funding support.

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