Development and Application of Planar Laser Thermometry in Sooting Flames

Doctoral Dissertation

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Abstract

Temperature may be considered the most important combustion parameter owing to its exponential influence on chemical reaction rates and on the formation of combustion products. However, reliable and detailed experimental temperature measurements are limited. Therefore, there is a strong need to develop a reliable temperature measurement technique for combustion environments that is relevant to practical devices such as turbulent sooting flames. This dissertation reports further development and application of a laser-based instantaneous temperature imaging technique called Non-linear excitation regime Two-Line Atomic Fluorescence (NTLAF) of indium in four journal papers. This dissertation, first, provides a new understanding of the mechanisms behind a novel seeding method employed in the NTLAF technique. Second, new knowledge of interferences to the indium fluorescence in highly sooting flames was reported and an effective means to improve the precision and accuracy of the NTLAF technique was demonstrated. Third, the accuracy of the improved NTLAF technique in turbulent sooting flames was assessed by comparing results with those obtained by the German Aerospace Centre (DLR) group using an independent technique. Finally, a line-wise NTLAF technique, which enables flame temperature measurement in highly sooting flames under high-flux irradiation, has been demonstrated.

The mechanisms of a novel seeding arrangement for the NTLAF technique, indium nanoparticles seeding, have been investigated. It was found that the NTLAF signal generation is associated with the vapourisation of indium nanoparticles into the gas phase by thermal decomposition. In addition, laser-induced *in-situ* ablation of the indium nanoparticles within the flame can be a further source of indium fluorescence. This is only significant in the low temperature regions of the flame that are also near to the base of the flame and is expected to generally have only a small influence on the NTLAF's accuracy since these regions are mostly at a temperature that is below the threshold of the NTLAF technique of $\sim$ 800 K.

Spatially- and temporally-resolved spectral measurements were employed to characterise the spectral interferences to indium fluorescence. A set of narrow-band filters with a bandwidth of ~ 1.2 nm (full-width at half-maximum, FWHM) and a high peak transmission of $\sim 95\%$ was then used to suppress interferences based on the spectral characteristics of the interferences. In comparison to a previous NTLAF configuration with broad-band band-pass filters employed (FWHM = 10 nm and transmission of $\sim 50\%$), it was found that the measurement accuracy was improved from 198 K to 10 K at a location where the soot volume fraction is 1.2 ppm. An average reduction of 40% in the standard deviation of measured temperature in single-shot measurements has also been achieved with the use of high transmission filters.

The accuracy of the improved NTLAF technique was assessed by performing planar measurements of temperature in a well characterised, lifted ethylene jet flame with a peak mean soot volume fraction of ~ 0.52 ppm and comparing these results with previous measurements obtained by the DLR group with Coherent Anti-Stokes Raman Scattering (CARS). Good agreement was found between the temperature results obtained with these two techniques, especially within a large central region of the flame in which a high probability of strong NTLAF signal occurs. In addition, measurements of planar soot volume fraction were simultaneously performed with the temperature measurements. It has been found that the joint probability of temperature and soot volume fraction depends more strongly on axial than on radial distance, consistent with previous trends found in other flames.

A line-wise NTLAF technique has also been developed to enable flame temperature measurement in highly sooting flames under high-flux irradiation, which is relevant to conditions in high temperature, solar receiver-combustors. Flame temperature was measured at various heights, with and without high-flux irradiation. The strong scattering interference to the NTLAF signal from the irradiated soot particles was accounted for by subtracting the scattering background. At a flame height of 40 mm and $r = 0$ mm, the temperature measurement probability distribution had a standard deviation of 40 K, or 2.2%, while the measurement accuracy due to the presence of unaccounted spectral interferences was about $\pm$ 45 K. The high-flux solar irradiation was also found to increase the temperature of the flame by up to ~ 100 K at heights above burner (HAB) between 26 mm and 41 mm and by ~ 50 K elsewhere on the centreline. The radial profiles of temperature show similar trends.

The first contribution of this dissertation is that the mechanisms of a novel seeding method for the NTLAF technique, indium nanoparticles seeding, have been found to be associated with vapourisation and *in-situ* laser ablation of indium nanoparticles. The influence of this seeding method on the accuracy of the NTLAF technique was found to be negligible in the regions where the indium nanoparticles decompose completely. The second major contribution is characterisation of the interferences to the indium fluorescence for the NTLAF technique, which leads to the improvement of accuracy and precision of the NTLAF technique in highly sooting flames with the use of a set of narrow-band filters. The accuracy and precision of the improved NTLAF technique for turbulent sooting flames was then assessed by performing temperature measurements in a well characterised, lifted ethylene jet flame and comparing temperature results with previous CARS data. This comparison confirms good agreement between the two methods within a large central region of the flame. Soot volume fraction measurements were simultaneously performed in this flame to advance understanding of soot evolution in turbulent sooting flames. It has been found that the joint probability of temperature and soot volume fraction depends more strongly on axial than on radial distance. Lastly, a line-wise NTLAF technique has also been developed to enable temperature measurement in highly sooting flames under high-flux irradiation, which is relevant to conditions in high temperature, solar receiver-combustors.

List of papers

[1] D. Gu, Z. Sun, P. R. Medwell, Z. T. Alwahabi, B. B. Dally, G. J. Nathan, Mechanism for laser-induced fluorescence signal generation in a nanoparticle-seeded flow for planar flame thermometry, Applied Physics B 118 (2) (2015) 209–218.

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Other publications

[1] X. Dong, Z. Sun, D. Gu, P. J. Ashman, Z. T. Alwahabi, B. B. Dally, G. J. Nathan, The influence of high flux broadband irradiation on soot concentration and temperature of a sooty flame, Combustion and Flame 171 (2016) 103–111.

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[7] X. Dong, G. J. Nathan, S. M. Mahmoud, P. J. Ashman, D. Gu, B. B. Dally, Global characteristics of non-premixed jet flames of hydrogen–hydrocarbon blended fuels, Combustion and Flame 162 (4) (2015) 1326–1335.

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