A method for performing high accuracy temperature measurements in low-pressure sooting flames using two-line atomic fluorescence

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Abstract

We demonstrate a step change in the capability of diode laser excited two-line atomic fluorescence (TLAF) thermometry and show it is well-suited to the study of low-pressure sooting flames. The new developments to the technique reported here were essential to achieve the accuracy (±41 K) and precision (±8 K) required for useful measurements in such systems. This represents the first application of TLAF thermometry to the investigation of low-pressure sooting flames, an environment in which other thermometry techniques perform poorly. We thus demonstrate a practical application of diode laser TLAF to a burner that is the subject of a coordinated experimental and computational investigation of soot formation. The TLAF technique requires no calibration measurement and is compact and economical to set up in comparison with traditional laser thermometry methods. Temperature profiles were recorded in a laminar flat-flame operating on O_2, N_2 and CH_4 at fuel equivalence ratio of 2.32 and pressures ranging from 18.7 to 26.7 kPa. Almost identical temperature profiles were observed at different pressures despite the fact that soot volume fractions changed by more than an order of magnitude between the lowest and highest operating pressures. The data will contribute to modelling efforts to understand the surprisingly strong dependence of soot volume fraction on pressure that has previously been observed under the range of conditions studied here and will be included in an openly available database on this flame, which includes species profile measurements obtained by other methods. In the current contribution we emphasise the technical implementation of diode TLAF as a new temperature diagnostic with near optimal characteristics for the study of low pressure, sooting flames.
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1. Introduction

The availability of high-quality temperature data is particularly important to the study of sooting flames, due to the dominant influence of temperature on all of the chemical and physical processes involved in soot formation. Experimental studies are often conducted in flat-flames, using laser diagnostics to make spatially-resolved, non-intrusive temperature measurements [1], but these are prone to problems in fuel-rich conditions and at low pressure. Improvements in laser diagnostic techniques are thus essential to accelerate progress in this field of research.

A range of laser based flame thermometry methods is available (reviewed elsewhere [2,3]), all with problems in low-pressure sooting flames. Rayleigh and Raman scattering yield low signal levels and suffer from interference due to elastic scattering of laser light from particulate material. These methods are thus better suited to diagnostics of 'clean' flames and have received little or no attention in the context of low-pressure sooting flames. Interference due to scattering can be avoided by performing filtered Rayleigh scattering, which has been used for temperature imaging in atmospheric-pressure sooting flames [4]. Filtered Rayleigh scattering thermometry involves the use of a single-mode laser and a narrow-line filter to block light scattered from slow-moving particles. It has not been adopted in the study of low-pressure sooting flames, where the need to block out part of the already weak signal might make it unattractive. Coherent anti-Stokes Raman scattering (CARS), also suffers in low pressure environments because of the non-linear dependence of the signal on number density. A further issue is the interference caused by laser-induced breakdown of soot to form C_2 whose emission in the Swan bands overlaps with the commonly-used CARS signal wavelength near 473 nm [5].

Successful temperature measurements have been reported in low-pressure flames by laser-induced fluorescence (LIF) of OH and of NO [6–8], although these refer to non-sooting flames. In fuel-rich flames the abundance of OH is very low and typically insufficient for measurements to be made at temperatures below 1600 K [8]. Thermometry by NO LIF [7,8] is performed by seeding nitric oxide to the flame in concentrations ranging between 0.2% and 1% leading to acceptable signal levels from the reaction zone but rapidly diminishing signals downstream of the flame front, because of nitric oxide reburning reactions [9]. It is nevertheless very important to obtain temperature data in the downstream region where the growth of large aromatic molecules and soot takes place. Some authors have, therefore, combined NO and OH LIF in order to achieve a full temperature profile in rich non-sooting flames [8]. Both OH and NO LIF require the use of bulky and expensive equipment and are typically performed by scanning the wavelength of light from a low repetition-rate pulsed dye laser over multiple absorption lines. Thermometry by OH LIF and NO LIF has rarely been implemented in low-pressure sooting flames, although NO LIF temperature measurements have been demonstrated in atmospheric-pressure and high-pressure sooting flames [10,11], as well as low-pressure hydrogen flames laden with TiO_2 particles [12]. Temperature measurements by OH LIF in low-pressure sooting flames were reported recently [13] with a precision of ±110 K quoted for data obtained from the reaction zone and from the luminous region where soot is present.

In addition to optical thermometry techniques, thermocouples have also been used to measure temperature in sooting flames. These are subject to numerous sources of error including catalytic, conductive and radiative effects. In sooting flames the thermocouple also becomes coated with particles. Although the latter error can be addressed by use of the rapid thermocouple insertion procedure [14], the systematic errors associated with thermocouple measurements are appreciable and the overall accuracy may be around ±100 K.

In this paper we present an alternative thermometry technique that combines excellent accuracy and precision with a relatively compact and inexpensive set-up. We demonstrate here the first application of two-line atomic fluorescence (TLAF) to temperature measurements in low-pressure sooting flames and show that it is particularly well-suited to these conditions. The technique is based on the seeding of indium atoms into the flame as a temperature probe [15–23]. The local flame temperature is obtained from the ratio of fluorescence signals emitted upon excitation of indium from the two spin–orbit split sublevels of its ground state (corresponding to the $5^2P_{1/2} \rightarrow 6^2S_{1/2}$ and $5^2P_{3/2} \rightarrow 6^2S_{1/2}$ transitions near 410 and 451 nm, respectively). In traditional implementations of TLAF [20,21], the $5^2P_{1/2} \rightarrow 6^2S_{1/2}$ transition is excited first with a laser line at 410 nm and fluorescence is detected at 451 nm; subsequently a 451 nm laser line is used to excite the $5^2P_{3/2} \rightarrow 6^2S_{1/2}$ transition and fluorescence is detected at 410 nm. A ratio of the two signals is a measure of the relative populations in the two lower states and in thermal equilibrium this provides a measure of temperature. Indium is a sensitive probe species for flames because the separation between the $5^2P_{1/2}$ and $5^2P_{3/2}$ is roughly equal to kT at flame temperatures. The TLAF technique is insensitive to the effects of quenching because the two transitions probed share a common upper state [15]. Of course, the use of an atomic probe species also avoids the errors that can result from vibrational and rotational energy transfer in thermometry based on molecular fluorescence.

In the past, we have also worked on temperature measurements based on one-line atomic fluorescence (OLAF) where the temperature is deduced form the atomic lineshape [24]. This provides a simple way to measure flame temperature using a single diode laser, which we have demonstrated both in atmospheric-pressure and low-pressure flames [24,25]. Nevertheless, the lineshape analysis relies on there being a high mole fraction of nitrogen throughout the flame so it would not provide accurate results in the sooting flames studied here, which are low in N_2 diluent. The ratiometric TLAF approach described in the present paper is based on a completely separate measurement principle and the low mole fraction of nitrogen is therefore not a problem.

The potential of TLAF for temperature measurements in atmospheric-pressure sooting flames has been demonstrated in the past [20,21]. These studies involved the use of pulsed dye lasers to perform planar imaging. Although the method has the advantage of providing two-dimensional temperature maps of the flame, its precision was restricted to around 4% [21]. Because two detector systems with different efficiencies were used to collect the fluorescence signals (as is always the case in imaging TLAF), it was necessary to calibrate the technique using another thermometry method. This introduces calibration errors. The absolute accuracy was furthermore limited because the spectral linewidth of pulsed dye lasers is typically comparable to the linewidths of the probed indium transitions. The spectral overlap between the laser and the indium lineshapes is associated with uncertainty and may drift over time causing unaccountable systematic errors. As a result, the methods reported in [13,14] are very useful to provide qualitative temperature distributions in turbulent flames and engines but are not capable of generating sufficiently accurate temperature data for chemical kinetic studies of soot-producing model flames.

In this paper we make significant developments to a variant of TLAF which overcomes these limitations and which does not require a calibration measurement. We make use of low-cost and compact blue diode lasers for highly accurate and reproducible temperature measurements, a concept we have reported in a previous publication [22]. The high transition probability of atoms ensures strong fluorescence signals even when low-power, continuous-wave lasers are used for excitation. Blue extended-cavity diode lasers (ECDLs) with favourable wavelength tuning ranges were developed specifically for the purpose of TLAF temperature measurements [26]. The narrow-linewidth and tuneability of the blue ECDLs allow the spectra of indium to be fully resolved, thus permitting more accurate measurements to be performed than have been achievable with dye lasers. In a previous paper [22] we have used these lasers to perform TLAF using a single detector, thus making the technique calibration-free. In this approach, a 410 nm diode laser is used to excite the $5^2P_{1/2} \rightarrow 6^2S_{1/2}$ transition and fluorescence is detected at 451 nm; then a 451 nm diode laser is used to excite the $5^2P_{3/2} \rightarrow 6^2S_{1/2}$ transition and fluorescence is detected again at 451 nm using the same collection lens, filter and detector. We demonstrate here that single-detector TLAF works very effectively in low-pressure sooting flames because, for all flame conditions studied, the intensity of elastically scattered light was insignificant compared to the strong atomic fluorescence signal. For this form of TLAF, the temperature can be calculated as follows [22]:

$$T = \frac{\Delta E / k}{\ln\left(\frac{\int_0^\infty \frac{F_a(v)}{I_{13}(v)} dv}{\int_0^\infty \frac{F_b(v)}{I_{23}(v)} dv}\right) + 3\ln\left(\frac{\lambda_{32}}{\lambda_{31}}\right) + \ln\left(\frac{A_{32}}{A_{31}}\right)} \quad (1)$$

Here ΔE is the energy spacing between the ground states of the probed transitions, k is the Boltzmann constant, F_a and F_b refer to the fluorescence signals resulting from 410.2 nm and 451.1 nm excitation, respectively, I_{13} and I_{23} are the intensities of the 410.2 nm and 451.1 nm lasers, λ_{31} and λ_{32} are the wavelengths of the transitions (410.18 and 451.13 nm) and A_{31} and A_{32} are the coefficients of spontaneous emission. The ratio of the A coefficients is $A_{32}/A_{31} = 1.80$ [27,28]. The uncertainty in this ratio was quoted as $\pm3\%$ [15]; this contributes an uncertainty of ±30 K to the temperature measurements in the burnt gases (at 1800 K). A slightly different value for the ratio of the A coefficients of atomic indium has been used in previous TLAF publications ($A_{32}/A_{31} = 1.82$) but the discrepancy not significant since it is well within the 3% margin of error. The form of the TLAF expression shown in Eq. (1) is appropriate to diode laser TLAF, in which high-resolution fluorescence spectra are acquired by wavelength tuning the narrow-linewidth excitation sources. It includes integrals to reflect the fact that it is the integrals of the normalised fluorescence spectra that are used in the calculation of temperature.

In the present study we apply the technique to a model flame used for the study of soot formation at low pressure [29] and give a detailed account on how to perform these measurements to achieve optimal accuracy and precision. The burner used has been subject to systematic studies of soot formation involving a range of laser diagnostic techniques and the data is being modelled extensively. Results on laser-induced incandescence [29] and on species-selective laser-induced fluorescence of polycyclic aromatic hydrocarbons [30] have been published recently. Of particular interest was the finding that the soot volume fraction f_v in the methane–oxygen–nitrogen flat-flame at a pressure of between 18.7 and 26.7 kPa (with

feed-gas composition held constant) exhibits an extremely non-linear dependence on pressure, with a proportionality of $f_v \propto p^{11}$ [29]. It was thus of great interest to study potential associated temperature variations over this pressure range, in attempts to understand this unexpected pressure dependence. The objective was to make temperature measurements with accuracy approaching $\pm 2\%$ in order to fully resolve the flame temperature profile from around 1000 K near to the burner surface up to the region of soot nucleation and growth, which is situated well downstream of the maximum heat release contour of the flame.

In this paper we first present a description of the experimental methods in which we focus on the modifications to the TLAF technique that have been necessary to improve the accuracy and precision. Temperature profiles recorded at a range of pressures and at a range of equivalence ratios in the flat-flame are then shown, along with OH laser induced fluorescence profiles recorded in the same flame. The temperature profiles are available in the Supplementary data, which accompanies this manuscript.

2. Experimental methods

Experiments were performed in laminar flat-flames of premixed CH_4, O_2 and N_2, stabilised on a water-cooled McKenna burner situated in a low-pressure chamber. All gas flow rates were regulated by mass-flow controllers. The porous-plug had a diameter of 60 mm and was surrounded by a co-annular flow of N_2. The low-pressure chamber was equipped with optical access via four windows. The burner system and conditions prevailing were identical to the ones used in other studies recently reported by the Lille group [29,30]; temperature profiles reported here thus contribute optimally to the interpretation of existing datasets. The sets of flame conditions studied are summarised in Table 1.

The set-up for the diode laser TLAF measurements is shown in Fig. 1. Beams from two blue diode lasers emitting at 410.2 and 451.1 nm [26] were superimposed using a dichroic mirror. The overlapped beams were focussed to a waist of around 100 μm at the central vertical axis of the burner and the focal region was imaged through an interference filter ($\lambda_c = 451.1$ nm; $\Delta\lambda = 3$ nm)

and horizontal slit (500 μm high × 10 mm long) onto a photomultiplier tube. This resulted in a spatial resolution of around 100 μm in the vertical direction (determined by the size of the laser focus), which is sufficient to fully resolve the temperature gradient even in the reaction zone of the low-pressure flame. The lower spatial resolution of 10 mm in the horizontal direction is acceptable in this flame since there are negligible radial gradients near to the burner centre-line at all locations where measurements were taken. Excitation was performed with maximum irradiance of about 8 W cm^{-2}, which is well below the saturation limit.

Just as in our previous studies, indium was seeded to the flame by passing a part of the feed gases through a spray-type nebulizer (Agar Scientific B701 Microspray). The nebulizer consisted of a nozzle of about 0.7 mm diameter situated above a capillary (also about 0.7 mm inner diameter). The capillary descended into an aqueous solution of $InCl_3$ whose concentration was adjusted to achieve a seeding level sufficient to yield strong fluorescence signals without, however, causing measurable attenuation of the incident beam by atomic absorption. The fine droplets leaving the nebulizer evaporate to give solid indium chloride particles that are entrained in the flow. The $InCl_3$ appeared to pass through the porous burner plate of the McKenna burner without deposits forming or other recognisable problems(different burner types including capillary-hole flat-flame burners [31] had been used in previous diode laser atomic fluorescence studies). The seeding process results in the addition of about 0.1 slpm (standard litres per minute) water vapour to the premixed feed gases, corresponding to a mole fraction of 2%. We have estimated that this mole fraction of water vapour would influence the flame temperature by less than ± 20 K [25].

The potential influence of the seeded indium on the flame temperature profile must also be considered. The introduction of metal atoms [32] or metallic complexes [33] to flames may influence the concentrations of aromatic species and soot. Nevertheless, the concentrations of dopants typically added in those studies are three orders of magnitude greater than the concentration of seeded indium that was used during the present study (<100 ppb). We do not expect soot formation to be measurably enhanced by the presence

Table 1
Summary of the total pressure and feed-gas composition for the four flames studied. The volumetric flowrates are specified in standard litres per minute (slpm).

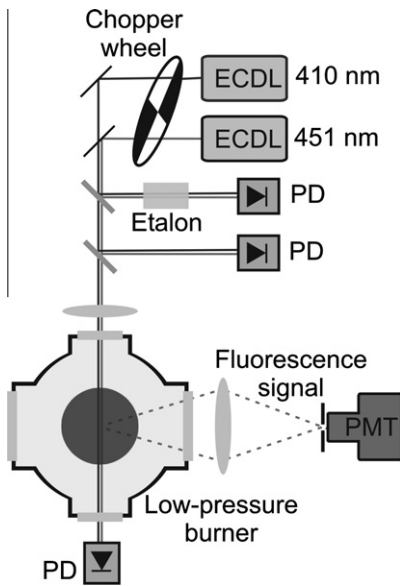|	φ	p (kPa)	Mole fractions			Total flow rate of reactants (slpm)	Flowrate of N_2 coflow (slpm)
			CH_4	O_2	N_2		
Flame A	2.32	26.7	0.46	0.40	0.14	4.11	5.40
Flame B	2.32	21.3	0.46	0.40	0.14	4.11	5.40
Flame C	2.32	18.7	0.46	0.40	0.14	4.11	5.40

Fig. 1. The set-up for TLAF thermometry in a low-pressure sooting flame. ECDL: extended-cavity diode laser; PMT: photomultiplier tube; and PD: photo-diode.

of indium since the quantity added is so low. Any effect of indium on heat loss through radiation is therefore expected to be negligible, particularly given the low soot volume fraction in the flames studied here. If the concentration of seeded indium is maintained below 100 ppb it seems likely that this would not be a significant source of error even for temperature measurements in highly sooting flames.

The temperature is calculated from the ratio of fluorescence signals resulting from the two excitation wavelengths (see Eq. (1)). This means it is vital that the concentration of seeded indium in the flame does not drift between one excitation

and the other [34]. In earlier measurements [22] there was a delay of about a minute between the excitation with one laser and the other, which could result in appreciable errors if seeding fluxes were not absolutely stable.

A new approach was therefore adopted in which spectra were recorded by scanning the wavelengths of both lasers at 10 Hz and switching between the two beams at the same rate using an optical chopper, as shown in Fig. 1. Example traces of the raw data obtained by this method are shown in Fig. 2, which displays the average of 50 scanning cycles and thus took 5 s to record. The data shown were recorded in flame A (see Table 1: $\varphi = 2.32$, $p = 26.7$ kPa) at 40 mm above the burner surface. The fluorescence spectrum of the $5^2P_{1/2} \rightarrow 6^2S_{1/2}$ transition appears on the left and the $5^2P_{3/2} \rightarrow 6^2S_{1/2}$ transition on the right. Alternating excitation/detection cycles between the two transitions in this fashion makes the technique immune to drifts in indium concentration and thus entirely eliminates this source of inaccuracy.

Also shown in Fig. 2 are plots of the simultaneously recorded laser power and of the etalon transmission used to convert the time axis into a frequency scale. The laser intensity normalised fluorescence spectra were used to calculate temperature by fitting theoretical spectra comprising a sum of Voigt profiles representing the hyperfine components of the transitions. Equation (1) was then used to calculate temperature based on the integrated theoretical spectra. It should be noted that elastic scattering from particulates in the flame makes very little contribution to the baseline of the spectra for the $5^2P_{3/2} \rightarrow 6^2S_{1/2}$ transition at 451 nm, despite the fact that resonance fluorescence is being detected. The spectra shown in Fig. 2 were recorded in the most sooting flame that was studied, at a location where the soot volume fraction is approximately 1.0×10^{-9} [29].
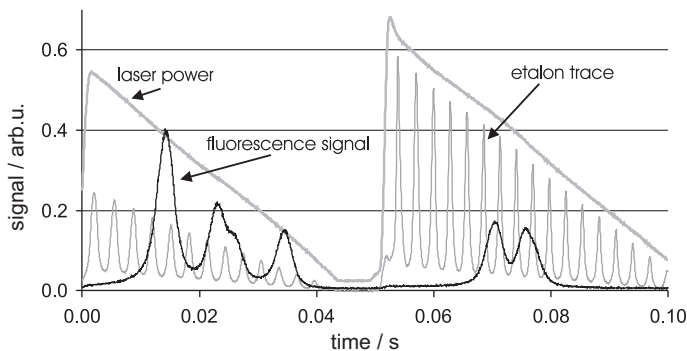

Fig. 2. Raw data for the fluorescence signal, laser power reference measurement and etalon transmission, showing the average of 50 wavelengths scans. The signals in the left-hand part of the figure are generated by the 410.2 nm laser. As it reaches the end of its wavelength scan, it is blocked by the chopper. Then the 451.1 nm laser is transmitted instead, generating the signals seen in the right-hand part of the figure. These signals were recorded at a height of 40 mm above the burner in the flame with $\varphi = 2.32$ and $p = 26.7$ kPa.

The contribution of scattering, which would appear as a sloping baseline on the spectrum, is almost imperceptible. This demonstrates that the single-detector TLAF approach works well in low-pressure sooting flames, thus allowing a simple experimental set-up to be used and permitting accurate temperature data to be obtained without the need for a calibration measurement. As previously stated, measurements were made in flames with fairly low soot volume fraction because they are the subject of a wider study of soot formation, in which there was a strong requirement for accurate thermometry to use as input for numerical modelling. It seems clear that the single-detector approach would also work at significantly greater soot volume fractions, although TLAF thermometry would probably need to be performed using two detectors for measurements in the most highly sooting flames.

A potential source of error in TLAF thermometry results from imperfect spatial overlap between the exciting laser beams. This is particularly critical in the flame-front region, where there are steep gradients in temperature and in indium concentration. At the imaged region it is thus critical that both the two beams are at precisely the same height above the burner. A razor edge was translated vertically across the width of the measurement volume to determine the location and the diameter of each beam in turn. Adjustments were made until the mismatch in beam heights was less than 10 μm. Similarly, it was ensured that the imaging slit was aligned parallel to the axis of the laser beams to ensure that no clipping occurred in the image of the beam foci.

Another potential source of error is the uncertainty in the measurement of laser powers, which is necessary in order to normalise the fluorescence spectra (see Eq. (1)). In previous work we used a photodiode-based laser power meter, whose reading is strongly wavelength dependent. This resulted in an estimated systematic error of

around 7% in measured temperatures [22]. In the present work we have used a thermopile power meter (CVI Melles Griot, 13 PEM 001/J) whose reading is not wavelength dependent. The resulting uncertainty in measuring the ratio of laser powers is below 2% in the current set-up, corresponding to an error in temperature of 18 K in the burnt gases (at 1800 K).

We also performed measurements of OH laser induced fluorescence in the flame at 26.7 kPa with $\varphi = 2.32$ (flame A – see Table 1). The output of a frequency doubled dye laser was tuned to coincide with the $Q_1(6)$ line of the $A^2\Sigma(v' = 0) \leftarrow X^2\Pi(v'' = 0)$ transition of OH near 308.8 nm. The beam was focussed at the centre-line of the burner and the focal region was imaged onto the entrance slit of a monochromator, which was used to exclude scattered laser light. The fluorescence signal was detected using a photomultiplier tube. The laser energy was attenuated to ensure that the excitation was being performed within the linear regime.

3. Results and discussion

Measured flame temperatures are shown in Fig. 3 for three different pressures of 18.7 kPa, 21.3 kPa and 26.7 kPa; it is observed that the temperature profiles for these three flames are very similar to each other. The excellent precision that is achieved due to the improvements to the TLAF technique is apparent from the smoothness of the plots in the burnt gas region. This allows the very slight differences between the three temperature profiles to be revealed. The 18.7 kPa flame appears to be about 35 K hotter than the 26.7 kPa flame in the burnt gases (height above burner $\geqslant 6$ mm), with the profiles converging slightly at higher elevations above the burner. It can be seen from the location of the steep rise in temperature that the 26.7 kPa flame lies closest
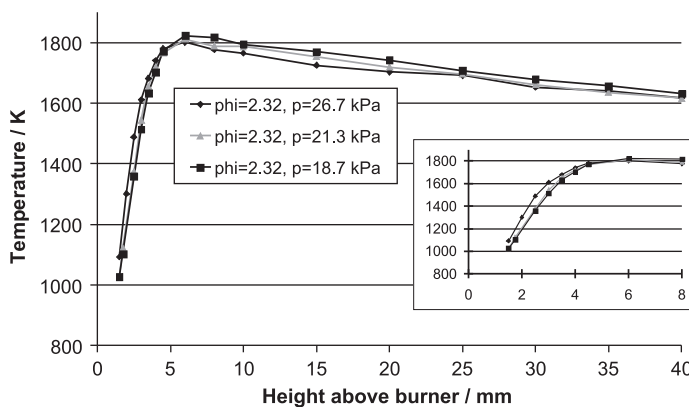

Fig. 3. Temperature profiles for flames at pressures of 18.7, 21.3 and 26.7 kPa with $\varphi = 2.32$. The insert shows an expanded view of the temperature profile at the reaction zone.

to the burner. By comparison, the reaction zone of the 18.7 kPa flame seems to lie roughly 0.5 mm further from the burner. The temperature profile of the flame at an intermediate pressure of 21.3 kPa appears to lie between those of the other two flame conditions. Although the ability to identify slight differences between the temperature profiles highlights the fidelity of the technique, the main observation is that the flame temperature profile does not change strongly with pressure over the range of conditions studied.

By fitting a straight line through the datapoints in the burnt gases and calculating the standard deviation of the absolute residuals, the precision was found to be better than ± 8 K. Systematic errors were described above resulting from inaccuracies in the ratio of line-strengths, the effect of indium seeding and the measurement of the ratio of laser powers. These uncorrelated errors result in an estimated global uncertainty of up to ± 41 K in the burnt gas region. In the region of the reaction zone (height above burner <6 mm) an upper estimate of ± 24 K precision was calculated from the experimental data. This conclusion is corroborated by the fact that for all the measurement locations shown in Fig. 3 the signal levels were high enough to obtain good fits between theoretical spectra and the experimental data. An additional source of systematic error in the reaction zone results from the strong gradients in temperature and in seeded indium concentration. An upper limit has been placed on this error source by assuming that the misalignment between the foci of the two lasers may be up to 20 μm. This error source is only significant at less than 2.5 mm from the burner surface. At locations below 1.5 mm above the burner (<1000 K) this error source grows larger, making accurate thermometry difficult, since the indium concentration is low and rising very sharply. This temperature is just above the threshold for the decomposition of the seeded $InCl_3$ salt to form atomic indium. The temperature profile of the flame at 26.7 kPa is

shown again in Fig. 4 with error bars denoting the calculated global uncertainty at each datapoint.

The soot volume fraction measured by LII [29] in the 26.7 kPa flame is displayed together with the corresponding temperature profile in Fig. 4. The LII measurements have been extended slightly further downstream than the results published previously [29] and show that the rate of increase of soot volume fraction becomes less steep at these higher positions. The soot formation zone begins well downstream of the reaction zone at around 13 mm above the burner surface. The results of measurements of OH LIF for the 26.7 kPa flame are also shown in Fig. 4. It was found that the OH signal level would have been barely sufficient to perform thermometry even near to its peak concentration. Due to the steep decay in the OH LIF signal in the burnt gases and also to the interference from soot luminosity we observe that OH LIF thermometry would have very poor precision in the soot formation region of this low-pressure flame. The accurate diode laser TLAF temperature measurements that we have obtained throughout the flame are therefore crucial as input data for numerical modelling studies of PAH and soot formation.

4. Conclusion

Diode laser two-line atomic fluorescence has been used to make calibration-free temperature measurements in sooting flames with excellent accuracy and precision. The spatial resolution was sufficient to resolve the temperature profiles in the reaction zone of low-pressure sooting flames down to temperatures of around 1000 K. It was shown that the technique performs equally effectively in this environment as in open flames. Seeding of indium through the porous-plug McKenna burner was found to work well. The temperature profiles show very little scatter and the
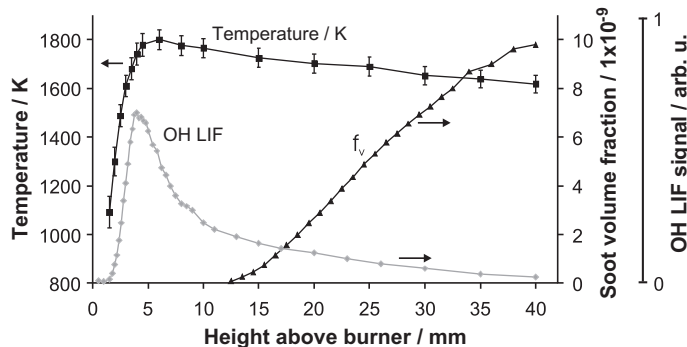

Fig. 4. Temperature profiles for flame at pressure of 26.7 kPa with $\varphi = 2.32$; error bars show the global uncertainty of the measurement at each position in the flame. Profiles of soot volume fraction (f_v) [29] and OH laser induced fluorescence (LIF) are also shown.

overall measurement accuracy is estimated to be about ±41 K in the burnt gas region, where soot is formed. An entire flame temperature profile can be recorded in about 30 min. The TLAF technique thus compares favourably to any other optical technique for thermometry in low-pressure sooting flames. Together with our recent results on high repetition-rate temperature measurements in acoustically pulsed flames [34], this demonstrates that the diode laser TLAF technique has now reached the point of maturity for application in a wide range of practical flames to provide temperature data of excellent accuracy in a compact and relatively simple set-up, that rivals traditional methods of combustion thermometry.

Acknowledgements

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.proci.2010.05.062.

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