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Optical thermometry for high temperature multiphase environments under high-flux irradiation

Dahe Gu [a,b,*], Zhiwei Sun [a,b], Graham J. Nathan [a,b], Xue Dong [a,c], Bassam B. Dally [a,b], Paul R. Medwell [a,b], Zeyad T. Alwahabi [a,c]

[a] Centre for Energy Technology, The University of Adelaide, S.A. 5005, Australia
[b] School of Mechanical Engineering, The University of Adelaide, S.A. 5005, Australia
[c] School of Chemical Engineering, The University of Adelaide, S.A. 5005, Australia

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ABSTRACT

A non-intrusive optical method to measure gas phase temperature in strongly scattering multiphase environments under high-flux, broad-band irradiation, relevant to conditions in high temperature solar reactors was developed and demonstrated. The high-flux irradiation with a peak flux of 450 kW/m^2 was provided by a 6 kW metal-halide lamp coupled with a reflector and two concentrators. An ethylene/air diffusion flame, which contains fine soot particles, was employed to provide a high temperature reacting flow (approximately 1800 K) with strong optical interference from nano particles having a peak soot volume fractions of ~16 ppm (with irradiation) under conditions of relevance to solar reactors. Under this environment, the proposed laser-based thermometry technique, line-wise two-line atomic fluorescence (TLAF) has been successfully demonstrated to measure flame temperature with good spatial resolution of ~1 mm. It was found that the measurement accuracy in the presence of particle and the high-flux external radiation is 65 K at a typical flame temperature of ~1800 K, while the measurement precision is 38 K. Results reveal that the presence of high-flux irradiation increases the flame temperature by typically 50–100 K. This paper presents a thermometry technique that is suitable for temperature measurement within solar reactors, particularly in hybrid solar-thermal receiver-combustor systems. The experimental setup, measurement methodology and data processing are discussed, followed by the temperature measurements.

1. Introduction

The utilisation of solar reactors to convert concentrated solar energy to chemical energy has been demonstrated to have potential for a wide range of applications, e.g. for hydrogen production (Abanades et al., 2007; Abanades and Flamant, 2007; Hirsch and Steinfeld, 2004; Moller and Palumbo, 2001), for metal production (Wieckert et al., 2007), the upgrading and decarbonizing of fossil fuels (Piatkowski et al., 2011; Steinberg, 1999) and in solar-combustion hybrids (Nathan et al., 2014). These devices usually feature a cavity-receiver configuration where concentrated solar energy is directed into a well-insulated enclosure through an aperture to drive the high-temperature chemical reactions. Compared with conventional fossil-fuel based processes, these solar-driven processes offer greatly reduced CO_2 emissions for high temperature processing (Steinfeld and Palumbo, 2001). Despite the recent demonstrations of pilot-scale solar reactor plants (Wieckert et al., 2007; Piatkowski, 2011) and experimentally validated modeling of a 1 MW design (Schunk et al., 2009), these technologies still require further development and optimization to become economically and technically viable for large-scale commercial applications. However, few, if any, detailed and spatially resolved measurements of the distribution of important parameters such as temperature, which controls the chemical reaction rate, are available (Abanades et al., 2007). Hence there is a need for accurate and spatially resolved gas temperature measurements in solar reactors.

Gas temperature measurement in solar reactors, however, is very challenging because of the high temperature environment, the presence of high-flux irradiation and, in some cases, the presence of fine particles. Solar reactors operate at temperatures between 1600 and 2400 K (Abanades et al., 2007; Abanades and

* Corresponding author at: Centre for Energy Technology, The University of Adelaide, S.A. 5005, Australia.
E-mail address: dahe.gu@adelaide.edu.au (D. Gu).

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Flamant, 2007; Hirsch and Steinfeld, 2004; Schunk et al., 2009; Müller et al., 2008), may also include fine particles with diameter ranging between 0.1 and 10 μm (Abanades et al., 2007; Hirsch and Steinfeld, 2004; Melchior and Steinfeld, 2008) and are subjected to a strong irradiation with flux ranging between 400 and 3500 kW/m^2 (Hirsch and Steinfeld, 2004; Moller and Palumbo, 2001; Müller et al., 2008; Piatkowski and Steinfeld, 2008). These make accurate gas temperature measurement very difficult to perform, particularly where they are spatially resolved. The presence of fine particles and high-flux irradiation not only inhabits the reliable application of probes, due to the direct exposure under irradiation and deposition of fine particles, but also hinders many optical methods due to the strong scattering. For these reasons, previous studies, typically only report the reactor wall surface temperature and a nominal cavity temperature obtained with the use of thermocouples (Abanades and Flamant, 2007; Hirsch and Steinfeld, 2004; Wieckert et al., 2007; Müller et al., 2008) or optical pyrometers (Abanades and Flamant, 2007; Hirsch and Steinfeld, 2004; Müller et al., 2008). However, the distribution of temperature is not homogeneous in a reactor cavity and the temperature of the gas is not as same as the wall temperature (Abanades et al., 2007; Müller et al., 2008). Hence there is a need for a thermometry technique that can provide spatially- and temporally-resolved temperature measurements as well as being non-intrusive to the flow field inside the solar reactors.

Laser diagnostic tools that are usually employed in the combustion research field may offer solutions to these problems, owing to their non-intrusive nature, together with their potential to provide good spatial and temporal resolution in high temperature environments (Aldén et al., 2011; Barlow, 2007; Daily, 1997; Nathan et al., 2012). However, the total radiative power in a solar reactor is much greater than the natural radiation from a soot-free flame, and even an order of magnitude greater than that from a sooting flame (Dong et al., 2015). This strongly radiative environment may reduce the accuracy and reliability of those laser-based optical thermometry techniques developed for combustion. To the best of the authors' knowledge, only coherent anti-Stokes Raman spectroscopy (CARS) has been successfully demonstrated to measure the gas temperature in a solar receiver/reactor to study gas phase chemical reactions in high temperature environment (Steinfeld et al., 1994). However, this study has only been demonstrated in an environment without any particles and was limited to point measurements with relatively poor spatial resolution. An alternative laser-based technique, two-line atomic fluorescence (TLAF) with seeded atomic indium as the tracer species, is also under development for two dimensional (2-D) temperature measurements in flames in the presence of fine particles (Chan et al., 2011; Engström et al., 2000; Gu et al., 2015; Kaminski et al., 1998; Manteghi et al., 2015; Medwell et al., 2013; Nguyen et al., 1996). However, this method has previously only been demonstrated in flames of moderate soot loading with peak concentrations of ~1 ppm due to the interference from scattering within nearby regions of a sheet that is inherent to planar imaging (Chan et al., 2011; Nguyen et al., 1996). There is potential to reduce this interference by changing the optical arrangement from planar to one dimensional. However, no previous assessments of the accuracy and precision of 1-D TLAF have been reported, particularly for soot loadings of ~10 ppm, as can occur in laminar flames, with or without the additional interference of external irradiation.

In light of the above background, the aims of the present study are to (1) demonstrate the application of one dimensional TLAF in high-temperature environments in the presence of both fine particles and high-flux external irradiation and (2) assess the precision and accuracy of the technique. The work also assesses the effect of high-flux irradiation on temperature of a typical diffusion sooting flame.

2. TLAF thermometry

In TLAF measurements, the gas phase temperature is derived from the intensity ratio between the two laser-induced fluorescence (LIF) signals of the tracer (e.g. atomic indium) excited from two different lower states to a common upper state. The population of the two lower states, which control the LIF signals, are related to the gas phase temperature according to the Boltzmann distribution law (Medwell et al., 2009). The gas temperature, T, can be calculated using the following equation,

$$T = \frac{\Delta E_{10}/k}{\ln\left(\frac{S_{21}}{S_{20}}\right) - \ln\left(\frac{F_{21}(E_{02})}{F_{20}(E_{12})}\right) + C_t}. \quad (1)$$

Here the subscripts 0 and 1 denote the two lower electronic energy levels while 2 denote the upper energy level, S is the collected LIF signal intensity, E is the laser spectral power density, ΔE_{10} is the difference in energy between electronic levels in [cm^{-1}] and has a value of 2212.599 cm^{-1} for atomic indium (Sansonetti and Martin, 2005), and k is the Boltzmann constant. The system-dependent dimensionless calibration constant, C_t, is dependent on a number of experimental factors such as solid angle of signal collection and collection efficiency of detector. The value of C_t needs to be experimentally determined through a calibration process, which is generally performed in a particle-free steady flame, where the temperature can be measured with a thermocouple. The value of C_t is a constant for a given optical arrangement and optical source. The term of $F(E)$ in Eq. (1) is used to correct for laser power variations during TLAF measurements, where F is the function of LIF signals dependent on the laser power E. The function F can be a linear function (i.e. for TLAF operating in the linear regime) (Engström et al., 2000; Nygren et al., 2001), a non-linear function (i.e. the non-linear TLAF) (Medwell et al., 2013) and even a constant (i.e. saturation TLAF) (Manteghi et al., 2015). The function F also needs to be determined from experiments. TLAF thermometry using atomic indium as tracer species is suitable for temperature measurements between 800 and 2800 K, which is well-matched to the temperature inside solar reactors.

3. Experimental details

3.1. TLAF setup

Fig. 1 presents a schematic diagram of the TLAF arrangement. Two Nd:YAG pumped dye lasers (Quantel, TDL 90) were employed to produce laser beams centred at 410.18 nm and 451.13 nm, respectively. Atomic indium in the flame was then excited to the same upper state ($6^2S_{1/2}$) from two lower states ($5^2P_{1/2}$ and $5^2P_{3/2}$). The laser pulse energies were kept at 1.0 μJ/pulse and 2.8 μJ/pulse, respectively. The two laser beams with a ~120 ns temporal separation were first combined using a dichroic mirror (Thorlabs, DMLP425) and then focused into round laser beams using a spherical lens (f = 1000 mm). The combined laser beams were directed through the centre of the burner and propagated at an angle of 30° relative to the central axis of the solar simulator. An aperture was placed 20 mm from the outer edge of the burner to reject stray light from the incident laser beams. The laser energy was monitored by recording laser beams reflected by a glass plate using a fast photomultiplier tube (PMT) coupled with a 2 GHz oscilloscope (LeCroy, 204MXi-A).

The two LIF signals were imaged using two intensified CCD (ICCD) cameras (Princeton Instruments, PI-MAX II) mounted with standard Nikon f/1.4 lenses (f = 50 mm). Two custom-made narrow-band filters (Alluxa) with a full width at half maximum (FWHM) of ~ 1.2 nm, a peak transmission of 95% and a high optical density (OD) of ~6.0 at the excitation laser wavelengths were used