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Non-intrusive temperature measurement of particles in a fluidised bed heated by well-characterised radiation

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ABSTRACT

We report an important step towards the in-situ measurement of heat transfer in particle-laden flows via direct measurement of the temperatures of fluidised particles. Laser-induced phosphorescence (LIP) was employed to provide non-intrusive, temporally resolved and in-situ measurement of suspended particles as a function of heat flux and radiation attenuation. Excitation was performed at 355 nm with a repetition rate of 1.67 Hz. Particles were transported with dry air within an optically-accessible fluidised bed and heated with a well-defined source of high-flux radiation from a 3 kW solid-state solar thermal simulator radiation to achieve heating rates in order 23,000°/s. Particle and gas temperatures were measured simultaneously with the former determined from thermo-phosphorescent emissions following excitation at 355 nm. Irradiation flux and mass loading were found to play important roles in particle and gas temperature rise. Confidence in the method was obtained by verifying internal consistency between the energy absorbed by the particles and the temperature rise of the gas phase, taking into account the variability of particle mass loading.

1. Introduction

In-situ and instantaneous measurement of the temperatures of micron-sized particles within a turbulent environment is challenging. Currently, all of the methods reported of a system that provides the direct temperature measurement of particles suspended in a turbulent flow have limited spatial and/or temporal resolution. Previous temperature measurement techniques developed have exploited the heat transfer relationship between the gas and solid-phases of a two-phase flow (Abram et al., 2013; Basu, 1990; Chen et al., 2006; Collier et al., 2004; Parmar and Hayhurst, 2002). In these cases, the solid particles within the flows are either assumed to be small enough for their heat transfer processes to be modelled as a gas (i.e. the two-phase effects are essentially neglected) (Abram et al., 2013; Hasegawa et al., 2007; Jovicic et al., 2015), or the temperature of the particles is inferred from fundamental heat transfer equations (Katoshevski et al., 2001; Lin, 1999; Mograbi et al., 2002). However, while these equations are well established for idealised conditions, they do not take into account the more complex effects such as the 2-way and 4-way coupling regimes in turbulent flows, which include particle-fluid coupling, inter-particle interactions and particle clustering. They also become inaccurate for high heating rates of particles in the order of 10,000 °C/s in applications such as solar receivers (Piatkowski et al., 2011), combustion (Müller et al., 2017) and gasification, both from solar and auto-thermal conditions using oxygen (van Eyk et al., 2016). Additionally, the analysis of Rosner and Park (1988) showed that a high particle mass loading in a thermophoretically-modified aerosol particle transport system increases exponentially the boundary layer wall heat transfer coefficient. Although this analysis does not investigate the effect of particle mass loading on the solid-phase heat transfer, it provides further evidence that the influence of particle mass loading should not be neglected. Hence, there is a need to demonstrate a more reliable thermometry method to directly measure the temperature of suspended particles without influencing the gas-phase.

In recent decades, laser diagnostic measurement techniques have been developed to provide the in-situ and high-speed measurement of an increasing number of parameters with high temporal resolution (Abram et al., 2013; Fond et al., 2012; Kohse-Höinghaus et al., 2005). One such technique of particular relevance to the measurement of particle temperature is laser-induced phosphorescence (LIP), which utilises the temperature-dependent properties of thermophosphors (TPs) to measure the temperature

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Nomenclature

FOH	Fibre-optic head
LIP	Laser-induced phosphorescence
SNR	Signal-to-noise
SSSTS	Solid-state solar thermal simulator
TP	Thermophosphor
$\dot{Q}_{att}$	Attenuated power [W]
$\dot{Q}_{conv,c}$	Convective cooling power [W]
$\dot{Q}_{gain}$	Power absorbed [W]
$\dot{Q}_{in}$	Power input [W]
$\dot{Q}_{out}$	Power output [W]
$\dot{Q}_{rad,h}$	Radiative heating power [W]
$\dot{Q}_{rad,c}$	Radiative cooling power [W]
$\bar{T}$	Average temperature [°C]
A_p	Particle surface area [m^2]
A_s	Cross-sectional laser sheet area [m^2]
c_p	Specific heat capacity [J/K]
d_p	Particle diameter [m]
h	Heat transfer coefficient [W]/m^{2}K
I	Intensity [count]
$\frac{I_1}{I_2}$	Intensity ratio
m	Particle mass [g]
Nu	Nusselt number
P	Power [W]
T	Temperature [°C]
t	Time [s]
ΔT	Change in particle temperature with respect to room temperature [°C]
ε	Emissivity
λ	Wavelength [nm]
σ	Stephan-Boltzmann constant [W]/m^{2}K^4
χ	Attenuation
Φ	Heat flux [MW/m^2]

Subscripts

a	ambient
g	gas
p	particle

of particles. This technique requires an excitation source, such as laser radiation, to excite the TPs. Following excitation, the TPs emit phosphorescence, which is generated by the relaxation of electrons from the excited state to the ground state. The emission can then be collected using either an ICCD camera fitted with an image splitter, or with two ICCD cameras. An advantage of this technique is that phosphorescent materials have a lifetime close to the temporal resolution of typical intensified cameras (Charogiannis and Beyrau, 2013). This enables the maximum emission intensity to be collected during experiments. Furthermore, a large range of TPs that are available, each with their own operating temperature ranges and decay lifetimes (Aldén et al., 2011; Feist et al., 2003; Heyes et al., 2006). This offers the potential for a TP to be selected to match the expected temperature range on a case-by-case basis. Good accuracy can be anticipated given that errors in particle temperature measurements of between 5–10% have previously been reported in the previous studies of Abram et al. (2013) and Jovicic et al. (2015). However, the method is yet to be applied to resolve particle temperature in an environment in which the particles are at a significantly different temperature from that of the surrounding flow, notably in a system where the particles are simultaneously heated with a source of high flux radiation.

The present investigation employs a source of high-flux, well-characterised radiation at a wavelength of 910 nm that is absorbed only by the particle phase and not by the gas phase. Furthermore, the heat flux is sufficiently high for the difference between the particle temperature and the gas-phase temperature to be representative of conditions that occur in industrial systems. This is a challenge, given both the very short time-constants of small particles and the short residence times in turbulent flows [21, 24, 25]. The short residence time results from the need to use velocities of about 20 m/s or higher in a suspension flow to avoid particle fallout. This is achieved with a solid-state radiation source, which has only recently become available with sufficient power and intensity. The solid-state system reported by Alwahabi et al. (2016) provides 3 kW of continuous radiation at fluxes of up to 30,000 kW/m^2. This laser generates the opportunity to establish a system that can provide in-situ measurements of temperature under conditions in which the heat transfer between the gas phase and particle phase is both well characterised and significant.

The aim of the present investigation is to demonstrate a direct, non-intrusive, temporally resolved, in-situ particle temperature measurement simultaneously with radiation attenuation. The combined measurement would be a key step towards fully understanding heat transfer in particle-laden flows. More specifically, we aim to demonstrate a temporally-resolved, volume-averaged application of LIP (that is, averaged over a measurement volume that is larger than an individual particle) with particles heated with well-controlled high flux radiation. This paper further aims to experimentally verify the relationship of gas and particle temperature, where a two-phase thermometry is performed simultaneously.

2. Theoretical approach

To select an appropriate thermophosphor (TP) for the current investigation, an estimate of the expected temperature rise was required. This was obtained with a simple first-order heat transfer model of heat transfer to a single moving particle subjected to radiative heating at high fluxes, using with in-house Matlab codes. The model considers: (1) radiative heating of the particle, (2) convective cooling between the particle and surrounding flow, (3) reradiation, (4) heat gain within the particle. These heat transfer modes may be expressed with the following energy balance equation. The mentioned heat transfer modes may be expressed with the following energy balance equation:

$$\dot{Q}_{rad,h} = \dot{Q}_{conv,c} + \dot{Q}_{rad,c} + \dot{Q}_{gain} \tag{1}$$

where $\dot{Q}_{rad,h}$, $\dot{Q}_{conv,c}$, $\dot{Q}_{rad,c}$, and $\dot{Q}_{gain}$ are the radiative heating, convective and radiative losses, and particle heat gain respectively. Each of these processes can be expressed by the following equations:

Radiative heating:

$$\dot{Q}_{rad,h} = \varepsilon \frac{P}{A_s} A_p F_{12} \tag{2}$$

Convective cooling:

$$\dot{Q}_{conv,c} = hA_p(T_p - T_a) \tag{3}$$

Radiative cooling:

$$\dot{Q}_{rad,c} = \alpha\sigma A_p\left(T_p^4 - T_a^4\right) \tag{4}$$

Heat absorption:

$$\dot{Q}_{gain} = \dot{m}_P c_P \frac{d\left(T_{p,t} - T_{p,t-1}\right)}{dt} \tag{5}$$

where ε is the absorptivity specific to the particle material, $\frac{P}{A_s}$ is the energy flux from the radiative heat source (P is given by the power from the heat source, while A_s is the cross-sectional area of the heat source), $A_p = 4\pi r^2$ is the surface area of the particle