High-Speed Thermographic Particle Image Velocimetry

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Abstract Many turbulent flows of practical interest exhibit infrequent or oscillatory behaviour, such as flame extinction or instabilities in thermal boundary layers. Laser-based diagnostics applied at repetition rates commensurate with turbulent timescales provide completely new insight into these transient phenomena. Frequently, simultaneous scalar-velocity measurements are required to properly interpret high-speed (> kHz) imaging data, and despite recent advances, novel techniques for kHz-rate temperature imaging are still needed for flows involving heat transfer or chemical reactions.

In this paper, simultaneous temperature and velocity imaging using BAM:Eu thermographic phosphor particles seeded into the flow is demonstrated in turbulent gas flows at a 3 kHz repetition rate. The velocity field is measured using a standard high-speed particle image velocimetry approach. A frequency-tripled diode-pumped Nd:YAG laser is used to simultaneously excite the phosphor particles, and the temperature-sensitive phosphorescence emission is recorded with two high-speed CMOS cameras to determine the tracer temperature using a two-colour method. Micrometre-size particles are used, which rapidly assume the temperature and velocity of the surrounding gas.

The cameras are characterised for ratio-based imaging in terms of both linearity and frame-to-frame variations and shown to be suitable for quantitative measurements. A single shot temperature precision of better than 5% can be achieved at 500 K. Time-resolved measurements in the wake of a heated cylinder are presented, demonstrating the utility of these imaging diagnostics to observe transient, coupled heat and mass transfer phenomena.

1. Introduction

High repetition rate laser-based imaging techniques are emerging as essential tools for the investigation of turbulent flows involving heat transfer or chemical reactions. In addition to the valuable spatially-resolved information regarding the flow structure afforded by planar laser diagnostics in general, imaging at high repetition rates (typically > kHz) provides insight into unsteady flow behaviour which occurs over a range of temporal scales encountered in turbulent flows of practical interest.

The extension of some well-established low repetition rate techniques to high-speed measurements has been enabled by the development of both diode-pumped solid-state (DPSS) lasers and high framing rate CMOS cameras (Böhm et al. 2011, Sick 2013). Visualisation of transient or unpredictable events in turbulent flows often requires not only kHz repetition rates but also extended recording sequences, frequently termed “sustained” measurements of up to a few seconds duration, which cover a broad range of turbulent timescales. CMOS cameras are available with large onboard memory capable of storing thousands of high pixel resolution frames. This combination of long record duration and high repetition rate allows the rapid accumulation of statistics in fast non-stationary processes and the capture of rare occurrences such as engine misfire (Peterson et al. 2011). Imaging the flow behaviour preceding and during transient combustion events such as flame propagation (Trunk et al. 2013) and extinction (Böhm et al. 2009) can also be achieved by post-triggering a looped recording sequence. Data extracted from these extended imaging sequences can be conditioned in time (on a specific event) and space (location of a relevant flow feature), to statistically analyse particular phenomena. Dominating frequencies of coherent flow structures can be identified, such as those caused by thermoacoustic oscillations (Steinberg et al. 2010). Also, it is a priority to provide datasets for the validation of new numerical models, which enable predictive capability in engineering design. Large eddy simulations provide information on transient behaviour, and imaging time-series recorded at high repetition rates (and data derived from these) can be compared with the results of such simulations (Böhm et al. 2008).

Planar velocity measurements have been successfully performed at kHz repetition rates in a number of applications using particle image velocimetry (PIV), where micrometer-size particles or droplets are seeded into the flow and their movement is recorded to determine the velocity field. However, for scalar imaging the
adaptation of existing low repetition rate techniques is restricted by laser technology, particularly in terms of available pulse energies. Specialised “pulse-burst” laser systems permit measurements approaching MHz rates with pulse energies of hundreds of mJ, but are limited to short recording times of around 1 ms (Thurow et al. 2013). DPSS lasers can be operated continuously, but after harmonic generation produce around 1 – 10 mJ per pulse, preventing the use of techniques based on Raman or Rayleigh scattering. Therefore sustained time-resolved scalar imaging diagnostics are generally limited to laser induced fluorescence (LIF) of high quantum yield species. Several studies employed LIF of flame radicals (e.g. OH, CH) combined with stereoscopic PIV for time-resolved investigations of turbulent flame phenomena (Boxx et al. 2009; Stöhr et al. 2011; Johchi et al. 2012; Trunk et al. 2013). LIF of biacetyl (Fjardo et al. 2006; Smith and Sick 2007; Peterson and Sick 2009) or acetone (Gordon et al. 2009) has also been used for quantitative mixing measurements in free jets and internal combustion (IC) engines.

Temperature is a variable of critical interest in all flows involving chemical reactions or heat transfer. However, to date there are only two demonstrations of planar measurements at sustained kHz repetition rates (Cundy et al. 2011; Peterson et al. 2013). Both are based on laser induced fluorescence (LIF) of toluene seeded into the flow and a two-colour detection scheme which uses the red shift of the fluorescence spectrum with increasing temperature. This technique was first applied in a heated jet (Cundy et al. 2011) and later, in combination with PIV, to investigate the evolution of temperature stratification in a motored IC engine (Peterson et al. 2013). Detection of the toluene emission around 300 nm required the use of high-speed intensifiers, which are associated with nonlinearities and charge depletion effects (Weber et al. 2011; Sick 2013). Also, toluene fluorescence is strongly quenched by oxygen. The low pulse energy (~1 mJ) of the frequency-quadrupled DPSS laser used for excitation meant these measurements could only be performed in a nitrogen bath gas.

Alternative techniques for high-speed temperature imaging are still required. Also, many of the cited experiments demonstrate that simultaneous access to scalar and velocity fields is essential for the proper interpretation of high repetition rate imaging data. However, even at low repetition rates joint planar measurements of temperature and velocity are hard to achieve due to the presence of seeding particles that are necessary for PIV, which interfere with Raman and Rayleigh scattering-based thermometry. Currently, other low-speed thermometry techniques based on the fluorescence of molecular or atomic tracers or flame radicals would be particularly difficult to extend to sustained kHz rate measurements due to limitations of the available laser technology.

In recent years, simultaneous temperature and velocity imaging has been demonstrated at low repetition rates using a combined phosphor thermometry and PIV technique (Omran et al. 2008; Fond et al. 2012). “Thermographic PIV” is based on phosphor thermometers, which are solid materials with luminescence properties that can be exploited for remote thermometry. Micrometer-sized phosphor particles are seeded into gas flows and used as a tracer. Velocimetry is performed with a conventional PIV approach, using the Mie scattered light from the phosphor particles. Following simultaneous UV excitation, these particles emit phosphorescence with a temperature dependent emission spectrum. When two spectrally filtered images of the particle phosphorescence emission are recorded, the tracer temperature can be determined using a ratio-based method. The diameter of the particles is carefully chosen so that their velocity and temperature rapidly assume that of the surrounding gas.

This technique has several important advantages. The tracer materials are chemically inert and have a high melting point (2200 K), and for many phosphors the emission is insensitive to pressure and oxygen quenching, making them particularly suitable for reactive flow applications. In addition, many thermographic phosphors have relatively broad excitation spectra allowing direct excitation with solid-state lasers, and their subsequent emission is often in the visible range, permitting the use of non-intensified cameras.

There is a wide variety of thermographic phosphors with very different optical characteristics, and reported applications of gas-phase phosphor thermometry have employed different phosphors as a tracer material (e.g. Omran et al. 2008; Fond et al. 2012; Jenkins et al. 2012; Rothamer and Jordan 2012; Jordan and Rothamer 2013). The authors have previously used the phosphor BaMgAl10O17:Eu2+ (BAM:Eu), which has a short phosphorescence lifetime of 1 μs and a high quantum efficiency. These are important features that allow reasonable signal levels from dispersed particles in the gas-phase, where the integration (exposure) time of the measurement is limited and the particles must be small enough to accurately trace turbulent flow fluctuations, restricting the number of luminescent centres in the measurement probe volume.

BAM:Eu saturates (Fond et al. 2012). Fig. 1 indicates how the phosphorescence emission of BAM:Eu
particles seeded into a gas flow varies with laser fluence. The plot shows that at laser fluences around 2 mJ/cm² the phosphorescence signal no longer increases linearly with the laser energy.

![Graph showing phosphorescence emission intensity with increasing laser fluence](image)

**Fig. 1** Phosphorescence emission intensity with increasing laser fluence in the gas phase, indicating saturation of BAM:Eu particles

It has been shown previously, at low repetition rates (5 Hz), that even in this saturated fluence regime the benefits of the short lifetime and efficient phosphorescence transition of BAM:Eu allow enough signal for precise single shot temperature measurements (Fond at al. 2012). The frequency-tripled output of DPSS lasers, on the order of a few mJ, is sufficient to saturate this phosphor using light sheets a few hundred micrometres thick that are typically used in laser-based imaging experiments. Therefore, signal levels are not limited by the low pulse energies of high-speed lasers and the possibility of kHz rate thermometry and velocimetry arises.

Accordingly, here we present a high-speed measurement technique based on seeded BAM:Eu phosphor particles for simultaneous temperature and velocity imaging in turbulent gas flows. The performance of CMOS cameras for quantitative measurements is investigated and the single shot pixel-to-pixel precision of the temperature imaging technique at kHz repetition rates is assessed in a turbulent heated jet. The combined diagnostics are used to investigate unsteady heat transfer behind a heated cylinder in a cross flow, where time-resolved measurements of the temperature and velocity fields are presented.

### 2. Experimental Setup

Initial measurements were performed in an electrically heated jet of air (21 mm diameter, velocity of 7 m/s) surrounded by a room temperature co-flow (80 mm diameter, velocity of 0.5 m/s). In the second heat transfer study, the central nozzle was removed and a pipe of 6.25 mm diameter heated to 530 K was positioned horizontally above the co-flow as shown in Fig. 2. The free stream velocity was set to 1.6 m/s so at a temperature of 293 K the Reynolds number was around 700, resulting in irregular vortex shedding in the wake of the cylinder (Williamson 1996).

![Diagram of experimental setup](image)

**Fig. 2** Experimental setup

For flow measurements based on solid tracer particles, the particle temperature and velocity should match that of the gas. Micrometre-size particles are often used as a tracer for PIV and are considered to
follow fluctuations in flow velocity with sufficient accuracy, so conduction is the dominant mode of heat transfer between the gas and the particles. Based on a detailed heat transfer model it was previously shown that 2 µm phosphor particles can also accurately trace the gas temperature (Fond et al. 2012). In both test cases presented here, the gas streams were seeded with 2 µm BAM:Eu phosphor particles (Phosphor Technology, KEMK63/UF-P1) using reverse cyclone seeders.

For thermometry, the phosphor particles were excited using the third harmonic of a diode pumped Nd:YAG laser (JDSU, Q301) with a pulse duration of 25 ns and a pulse energy of 1.3 mJ at 3 kHz. The beam was expanded using a Galilean telescope of f = -50 mm and f = +250 mm lenses and then formed into a 600 µm thick and 50 mm high light sheet using f = -50 mm and f = +500 mm cylindrical lenses. The phosphorescence emission was detected by two non-intensified CMOS cameras (Photon SA5, 12 bit, 1024 x 1024 pixels), fitted with 50 mm f/1.4 Nikon lenses. The cameras were operated at 3 kHz with an exposure time of 9 µs. The actual measurement duration is determined by the phosphorescence decay time of BAM:Eu (1 µs at room temperature). A long pass dichroic 45° beamsplitter (Chroma T445LP) and two interference filters (Edmund Optics 466-40 nm and Chroma 420-30 nm) were used to separate and filter the two detection channels, as shown in Fig. 3. The entire camera/beamsplitter system was aligned using micrometer stages to minimize relative distortion and differences in light collection path.

![Image](image.png)

**Fig. 3** Left: normalized BAM:Eu emission spectra, plotted at 50 K temperature intervals. The transmission curves of the beamsplitter (green) and the two filters (blue and red) used in this study are superimposed on the spectra. Right: intensity ratio response, measured in the gas phase.

After acquisition, background images were recorded and subtracted from the image pairs. Images were then spatially overlapped using software-based mapping (LaVision, DaVis 7.2) based on images of a calibration target. A cutoff filter at 15 counts was applied (corresponding to three times the readout noise of the camera), followed by 4 x 4 digital binning and a 3 x 3 unweighted moving average filter. The final spatial resolution was 720 µm, experimentally determined by the full width half maximum of the line spread function measured using a scanning edge technique.

A ratio image was computed from each filtered image pair. A uniform beam profile is not required because this technique is based on a ratio of two images, but spatial non-uniformity in the relative light collection efficiency between the two cameras must still be accounted for. This was achieved by dividing each ratio image by an average ratio image obtained in the gas-phase at room temperature.

To calibrate the ratio response with temperature for this specific detection setup, a thermocouple was positioned in the measurement plane during steady operation of the jet at different exit temperatures. The thermocouple readings were compared to mean intensity ratios obtained at the same location and a quadratic fit to this calibration data (Fig. 3) was used to convert the ratio images to temperature.

For PIV, a dual-cavity, frequency doubled diode-pumped Nd:YAG laser (Edgewave, IS-611DE) was operated at 3 kHz with a pulse separation of 50 microseconds, equally bracketing the phosphorescence excitation light pulse. All lasers and cameras were triggered using a trigger clock and the start of the recording for the three cameras was synchronised via a custom-made manual trigger switch unit. The 532 nm laser beams were superimposed on the 355 nm beam using a dichroic mirror placed before the sheet optics, and the width of the 355 nm beam was adjusted with the telescope to match the thickness of the 532 nm sheets. Light scattered by the particles was imaged using a third CMOS camera (Photon SA1.1, 12 bit, 1024
x 1024 pixels) equipped with a Scheimpflug adapter, a 105 mm f/2.8 Nikon lens with the f-stop at f/11 and a 532-10 nm bandpass filter. The camera was operated at 6 kHz, with the pulse of each independently-triggered laser cavity positioned at the respective end and start of consecutive frames. This results in double-frame acquisition at the desired 3 kHz. This camera was positioned on the opposite side of the measurement plane at a 6° angle to prevent any interfering background reflections between the two detection systems. Particle images were mapped to the phosphorescence images and then processed using a multi-pass cross-correlation algorithm (DaVis 7.2, LaVision) with an interrogation window size of 32 x 32 and 50% overlap, resulting in a final vector spacing matching that of the temperature resolution (720 µm).

3. Results and Discussion

The architecture of CMOS cameras, where each pixel is read locally, can cause a number of issues related to nonlinearity and signal offset. These factors affect CMOS performance for quantitative diagnostics, and were previously investigated using a similar camera of an earlier generation (Photon SA1.1) (Weber et al. 2011). Nonlinearity was found be less than 5% over the maximum dynamic range of the camera (12 bits) and the pixel-to-pixel variation in gain was within 1%. In this study, these effects were expected to have little impact on the temperature measurement as the recorded intensity after dark image subtraction was always below 500 counts, where the reported nonlinearity is below 2%.

To support this assumption, the effects of nonlinear sensor response on the measured ratio were experimentally investigated for the Photon SA5 cameras used for thermometry. A phosphor pellet was placed behind two diffusive glass screens and illuminated by the laser at 100 Hz to prevent possible laser induced heating effects. As in later experiments, the cameras were allowed to thermally stabilize. Images of the phosphorescence emission were acquired using the single-camera system at a repetition rate of 3 kHz to exclude effects of different recording frequencies on camera performance. Different pulse energies of the laser were used to cover the range of phosphorescence signals encountered in the actual gas-phase measurements, with recorded intensities between 20 and 500 counts. Averages of 100 single shots were compiled for each illumination level to reduce the influence of statistical noise, and a homogeneously illuminated region of 600 x 600 pixels was then extracted from each average ratio image. The ratio is 0.2 at room temperature (see Fig. 3), so nonlinearity will be indicated by differences between spatially averaged ratios obtained at different illumination levels, and pixel-to-pixel variations in gain will be manifested in spatial variations when dividing two average ratio images.

The spatially averaged ratio at each illumination level differed by less than 0.1%, indicating that in this intensity range the overall variation in camera gain is negligible. The pixel-to-pixel standard deviation of the divided average ratio images was 3.1%. Both findings are in good agreement with the previously mentioned study (Weber et al. 2011), when propagating the uncertainties for comparison with the divided ratio image evaluation used here. The spatial variation in pixel gain was reduced to 0.6% after the images were processed, so no image correction was performed in the actual gas-phase experiments.

The camera supplier provides an intensity calibration feature to correct for differences in pixel gain and dark levels based on an acquired dark image. This was disabled for this study since it modifies the individual pixel gain after each calibration, which must be avoided for repeatability. Instead, a manual background subtraction was performed as described above.

Initial measurements also indicated frame-to-frame gain fluctuations across the entire chip causing frame-to-frame variation of the overall intensity ratio, which would ultimately result in an overall change in the mean measured temperature between frames. This effect was quantified using a stable tungsten light source placed behind a diffusive glass screen. Based on a homogeneously illuminated region comprised of 50 processed pixels in the centre of each intensity ratio image, the frame-to-frame standard deviation of the spatially averaged ratio was found to be 1.5%. This is larger than the single shot pixel-to-pixel standard deviation in the same area (0.7%), indicating these frame-to-frame fluctuations are an order of magnitude larger than the 0.01% expected when considering a statistical distribution of the sampled mean. To account for this effect in the present work, a region in the image at a known temperature was used to correct for frame-to-frame differences in the overall ratio. According to the manufacturer, the next generation of cameras features improved stability in the internal power supply, resulting in much smaller frame-to-frame gain fluctuations. This will decrease the measurement uncertainty caused by these fluctuations, which will eliminate the need for any correction procedure.
The single shot precision of the thermometry technique at 3 kHz was determined from imaging data recorded in the heated jet test case at four steady jet exit temperatures. Statistics based on 20,000 independent measurements taken from a region in the jet potential core were used to compile the histogram shown in Fig. 4. The single shot pixel-to-pixel standard deviation was found to be 4.9 K (1.7%), 7.8 K (2.2%), 9.2 K (2.2%) and 21.9 K (4.4%) at 293 K, 363 K, 423 K and 500 K respectively. Signal statistics predict an error of 3.8 K at 293 K, indicating these results are close to the noise limit. From repeated measurement sequences, the maximum deviation of the mean measured temperatures to the flow temperature indicated by a thermocouple positioned in the measurement plane was only 5 K.

![Fig. 4 Histograms of 20,000 independent temperature measurements, recorded at 3 kHz for each steady jet temperature](image)

This level of temperature precision is comparable with that achieved in a previous study using a low speed measurement system based on interline transfer CCD cameras and low repetition rate flashlamp-pumped solid-state lasers (Fond et al. 2012). Because BAM:Eu saturates, the low pulse energy of the high-speed laser (around two orders of magnitude lower than the laser used previously) is not the limiting factor determining signal levels. The phosphorescence emission intensity is comparable for the two cases as saturation can also be achieved with the high-speed 355 nm laser.

The readout noise of CMOS cameras is larger than that of the CCD cameras used previously. However, in this study this potential decrease in signal-to-noise ratio was compensated for by increasing the phosphorescence collection efficiency. The spectrally flat 50:50 beamsplitter used in the former study was replaced by a dichroic beamsplitter (Fig. 3), almost doubling the collection efficiency, and a filter with increased transmission and a larger passband was also used which increased the light level in one channel by an additional factor of four.

The pulse energy of the 355 nm laser is constant up to 10 kHz. Therefore, it should also be noted that the thermometry measurement could have been performed at frequencies up to 10 kHz (at reduced readout of 1024 x 744 pixels) without any decrease in the signal to noise ratio. In this experiment, the sampling rate for simultaneous measurements was limited by the PIV camera, which operated at nearly full frame readout to achieve comparable spatial resolution between the two measured fields.

To demonstrate the utility of the combined diagnostics for the investigation of unsteady heat transfer phenomena, the time-resolved temperature and velocity fields were measured in the wake of the heated cylinder described earlier. Fig. 5 shows eight temperature and velocity fields, each separated by 5 ms. The mean velocity field has been subtracted from the instantaneous fields to better visualize the movement of eddies, and only every fifteenth image from the original 3 kHz recording is displayed so that the cyclic vortex shedding can be seen. Counter-rotating eddies of hot gas are alternately shed from either side of the rear stagnation point, which then cool as they are convected away from the cylinder.

The recording rate surpasses that required to resolve the phenomena of interest in this heat transfer study, but kHz rates are appropriate for the measurement of unsteady flow behavior more frequently encountered in the study of turbulent flows of practical interest. The 3 kHz rate was deliberately used to demonstrate the high image quality that can be obtained with these diagnostics. A video of this flow covering 50 ms at the full 3 kHz recording rate, allowing the visualisation of two full vortex shedding cycles, has also been published online (Abram et al. 2013).
4. Conclusions

Simultaneous planar measurements of gas temperature and velocity were demonstrated at sustained kHz repetition rates, using phosphor thermometry and a conventional PIV approach based on a single seeded tracer. The setup requires high-speed solid-state lasers only and non-intensified high-speed cameras, similar to conventional kHz PIV systems. The CMOS cameras were characterised for ratio-based imaging and shown to be suitable for quantitative measurements. The use of a fast, high quantum yield phosphor tracer permits precise temperature measurements at kHz rates in an oxygen containing environment, despite the low pulse energy of the high-speed 355 nm laser. The study demonstrates the potential of this technique for time-resolved investigations of unsteady heat transfer phenomena.

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References


