Development of the Thermographic Laser Doppler Velocimetry Technique

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ABSTRACT

Simultaneous measurements of flow temperature and velocity are crucial in characterising turbulent heat transport processes. The advancement of particle-based velocimetry methods has provided both qualitative and quantitative description of turbulent flows. In recent studies, the use of thermographic phosphors particles as flow tracers further supports these advancements due to the additional temperature information they provide. These particles have been employed to obtain planar measurements of flow temperature and velocity in an approach termed thermographic particle image velocimetry. Similarly, a point-based measurement approach has been demonstrated to achieve simultaneous measurements of these flow vector-scalar properties.

This paper further describes and characterises the point-based joint measurement technique called thermographic laser Doppler velocimetry (thermographic LDV) technique for flow temperature and velocity measurements. The flow metrology uses both Mie-scattered light and the optical properties of the phosphorescence emission that results from successive interactions between continuous wave laser light and individual 2 µm BaMgAl₁₂O₁₉:Eu²⁺ thermographic phosphor particles, which are seeded into the flow as a tracer. Photomultipier tubes (PMTs) are used to detect the signals collected from the measurement volume. The flow velocity is determined from frequency of the Doppler bursts obtained when particles traverses the fringes of two crossed visible laser beams as in conventional LDV. Luminescence in the form of Gaussian bursts that occurs after excitation of the same particles by an overlapped UV laser beam is simultaneously detected. Flow temperatures are evaluated from these acquired luminescence signals using the two-colour ratio, where two PMTs, each fitted with interference filters, transmits different parts of the temperature dependent emission spectral profile. The ratio of the two detected intensities has a monotonic dependence on temperature and is used to infer the particle temperature using previously acquired calibration data.

Potential cross dependencies that affect temperature measurements such as seeding density and laser fluence are investigated. The technique is then applied to acquire combined vector-scalar profile measurement at the exit of turbulent heated jet to evaluate the accuracy of the temperature measurements. A deviation better than 2% is achieved between mean temperature profile measurements obtained using a thermocouple and the point-based technique. Thermographic LDV is shown to serve as a valuable tool to turbulent heat transfer research.
1. Introduction

The need to perform in-situ flow measurements using non-intrusive techniques is satisfied through optical diagnostics, where in numerous applications seeded particles are employed as a tracer of the flow field based on their interaction with laser light (see books [1,2]). In turbulent flow processes characterised by thermal mixing, the use of laser-based diagnostic techniques for measurements of flow temperature and velocity facilitates understanding the nature of the contribution of turbulence to heat transfer. Information provided by such joint vector-scalar measurement technique serves to validate numerical models developed to predict turbulent heat transfer and also enhance the design and optimisation of industrial flow equipment.

Thermographic phosphor particles are emerging as an important flow tracer for the measurement of gas temperatures and velocities. Thermographic phosphors are inorganic crystalline solids that are composed of a host material and often a deliberately added activator (dopant or impurity) which lends specific luminescence attributes. After optical excitation photoluminescence occurs as a result of forbidden or partially allowed electronic transitions (therefore, correctly termed phosphorescence) that takes place between different energy states. The properties of the luminescence emission e.g. the luminescence lifetime or emission spectrum are sensitive to temperature changes. By exciting the phosphor using a laser and detecting the luminescence emission the temperature may be determined using either of the two major approaches: temporal method or intensity (or two-colour) ratio method. Phosphor thermometry has been exploited to measure temperature in many applications [3-4].

Thermographic phosphor particles can be seeded into the flow in place of typical velocimetry seeding material. The Mie scattering signal can be used to determine the velocity, while the temperature dependent properties are probed to simultaneously determine the temperature. There are many benefits of using thermographic phosphors as sole tracers for the remote flow temperature and velocity measurement. Thermographic phosphors are chemically inert and can endure reactive and high temperature environments due to their high melting temperatures (>1900 K). They have a high signal or quantum yield, and are often insensitive to pressure and local gas composition [5,6]. Furthermore, many thermographic phosphors have a broad excitation spectrum, which means solid state lasers are a practical excitation source. The successful application of thermographic phosphors to measurement of gas properties is based on the basic principle that micron-size particles when seeded into the flow of interest, rapidly assume the flow temperature and velocity [7]. Thus, like in the use of conventional seeding particles for flow velocity measurements using well-established velocimetry techniques, the use of thermographic phosphors allows the non-intrusive simultaneous measurement of the flow temperature.
For turbulent flow characterisation, simultaneous flow temperature and velocity measurements have been performed using thermographic phosphor particles as tracers by employing a planar technique called thermographic particle image velocimetry [7-9]. Mie-scattered radiation from particles seeded in the flow and illuminated by a laser light sheet is used to track the movement of these particles, and hence the flow velocity as in the conventional particle image velocimetry. Simultaneously, from the same particles, luminescence that follows their excitation by a pulsed UV laser, provides information on the flow temperature. Time-averaged [8], and single shot measurements at 5 Hz [7] and at 3 kHz [9] have been demonstrated in turbulent heated jets.

Recently, the authors have shown the feasibility of obtaining temporally and spatially resolved point measurements of gas temperature and velocities using a technique termed the thermographic laser Doppler velocimetry (thermographic LDV) [10]. In this study, 2 µm BaMgAl\textsubscript{10}O\textsubscript{17}:Eu\textsuperscript{2+} (BAM:Eu\textsuperscript{2+}) phosphor particles were seeded in an electrically heated air jet. A combined measurement volume is created at the intersection of two visible (514.5 nm) continuous wave (CW) laser beams and a UV (375 nm) CW laser beam. Photomultiplier tubes were used to detect the optical signals, shown in figure 1, resulting from the interaction between laser light and individual seeded phosphor particles crossing this measurement volume. The flow velocity is determined from the frequency of the Doppler bursts obtained from light scattered by individual phosphor particles traversing the fringes like in conventional laser Doppler velocimetry. Luminescence in the form of Gaussian bursts that occurs during illumination of the same particles by a UV laser beam is simultaneously detected. Flow temperatures are evaluated from these acquired luminescence signals using the two-colour ratio, where two PMTs, each fitted with
interference filters, transmits different parts of the temperature dependent emission spectral profile as shown in figure 2. The ratio of the two detected intensities is used to infer the particle temperature using previously acquired calibration data. This technique offers a high spatial resolution with a probe volume of 150 µm x 150 µm x 250 µm, and would be particularly suitable for measurements near walls or when the optical access is restricted.

In this paper, we discuss the utility of the thermographic laser Doppler velocimetry (thermographic LDV) technique for point-based velocity and temperature measurements in gaseous flows. First we describe the measurement setup then investigate the potential influence of seeding density and laser fluence on temperature measurements. The technique is then applied to two turbulent heated jet test cases, for which radial profiles are measured in order to assess both accuracy and repeatability as well as to show the utility of the thermographic LDV technique for flow characterisation.

![Fig. 2 (a) Temperature dependent emission spectra (spectral resolution = 1 nm) of BAM:Eu²⁺ with superimposed transmission profiles of the filter combination. Filter 1: 425 nm-50 nm x TP445LP reflection, Filter 2: 466 nm-40 nm x TP445LP transmission (b) Calibrated ratio as a function of flow temperature obtained using the thermographic LDV technique [10].](image)

2. Experimental setup

2.1 Phosphor particles

A variety of thermographic phosphor particles have been used to facilitate flow characterisation and a summary of phosphors used in gas-phase thermometry is found in [5]. The use of 2 µm diameter BAM:Eu²⁺ particles was considered in this study. Theoretical models showed that these
particles accurately trace the gas temperature and flow velocity in most turbulent flows of interest [5]. BAM:Eu\(^{2+}\) is attractive for the point-based technique because of the high quantum yield (>90 %) of its broadband emission, with a peak around 445 nm in the blue spectral region of the electromagnetic spectrum. The high quantum yield is important because the precision of the thermometry technique is dependent on intensity of the emission from individual particles. Also, the 1 μs emission lifetime of BAM:Eu\(^{2+}\) at room temperature, which decreases with temperature, means that for a wide range of flow velocities most of the luminescence signal can be collected. Figure 2(a) shows normalised emission spectra obtained from a stack of BAM:Eu\(^{2+}\) powder at different temperatures, superimposed with the transmission profiles of appropriate filter combination used in the thermographic LDV technique to separate two spectral regions for intensity ratio analysis. Figure 2(b) shows a calibration curve of the evaluated ratio as a function of flow temperature taken from the measurements in the potential core of a heated air jet using the thermographic LDV technique [10]. For reference, from this filter combination and calibration data, at room temperature, a 2% change in the intensity ratio corresponds to a 5 K temperature change.

2.2 Laser and beam configuration

Our experimental setup is illustrated in figure 3. As shown, a one-component LDV system in its most simple form is built from two laser beams (514.5 nm, from an Argon Ion laser), separated by a distance of 36 mm and focused by a lens (f = 250 mm) to form a measuring volume at the intersection of the beams. Although the current system presents the direction ambiguity intrinsic to the well-established LDV technique, here we did not attempt to remove this ambiguity using a Bragg cell since the main point of this study is to accomplish simultaneous temperature measurements. A third beam from a 375 nm, 70 mW UV diode laser (PhoxX—Omicron Lasers) is superimposed on the LDV measuring volume using the same focusing lens. At the focus, the green and UV beams were measured to have a 1/e\(^2\) beam diameter of about 150 μm. To monitor the overlap of the three beams, a glass window was placed after the focusing lens, reflecting a portion of the beams toward a CCD equipped with neutral density filters mounted on a translation stage.
2.3 Signal detection system

An 85 mm (f/1.4D) Nikon camera lens was used to create a single optical detection path through which Mie-scattered light and phosphorescence emission from the probe volume were focused through a 200 μm slit. As described in [10], the minimum spot size created by the lens in the image plane is 150 μm resulting in an effective length of the measurement volume of 250 μm, respectively (both are 1/e^2 widths). With the streamwise and spanwise spatial resolution both being defined by the beam diameter (150 μm), the spatial resolution of our measurement is 150 μm × 150 μm × 250 μm [10]. The optical signals were collected from the slit and collimated by a plano-convex lens, f = 75 mm. The collimated light was spectrally separated by a long-pass dichroic beam splitter (Chroma—t500lp-irxrt-UF1), which transmits the Doppler bursts and reflects the phosphorescence light. The phosphorescence light was then spectrally separated using a combination of a long-pass dichroic beam splitter (Chroma—t445lp) and a pair of interference filters [Edmund Optics: 425–50 nm and 466–40 nm (notation is CWL-FWHM)] shown in figure 2. To remove any remaining scattered 375 nm light, a 400 nm long-pass coloured glass filter was placed in front of the t455lp.

A photomultiplier tube (PMT) (Thorlabs) fitted with a focusing lens (f = 50 mm), and a 514–10 nm filter was used to acquire the Doppler bursts from the scattered 514.5 nm light. Two other identical PMTs (Hamamatsu R955HA—PMT2 and PMT3) fitted with focusing lenses (f = 50 mm)
each received the phosphorescence from the respective spectral regions (PMT2: 425 nm and PMT3: 466 nm). These phosphorescence-detecting PMTs were operated at the same supply voltage of 500 V (gain $10^5$).

2.4 Data acquisition and processing

The outputs of the three PMTs were fed into three channels of a Tektronix DPO4054 oscilloscope to provide digitization of the signals. The oscilloscope was controlled by a MATLAB program developed to acquire and post-process the signals. The electrical output from PMT1 was terminated by the 50 Ω impedance on the oscilloscope to preserve the temporal resolution of the Doppler burst signals. The output voltages resulting from the spectrally separated signals from PMT2 and PMT3 were measured using a variable feed-through terminator (Thorlabs) to give an actual resistance of 9.9 kΩ, thereby providing high output voltage signals.

The burst signals were acquired as three waveforms containing simultaneous Doppler and two phosphorescence burst signals over record durations varying between 400 ms and 100 ms with respective sampling rates in the range 2.5 MS/s – 10 MS/s, depending on the Doppler frequency. Without laser illumination, background signals were also acquired in the same manner and subtracted. In order to identify the bursts in the subtracted waveforms, a cut-off filter set at 20 mV was applied on the phosphorescence bursts signal waveform, and a time window was created for each burst based on this filter. This time window allows each burst signal from the other waveforms to be identified and also isolated.

The flow velocity was obtained by applying a fast Fourier transform (FFT) algorithm on each Doppler burst within each time window defined from the luminescence signals as described above. Within the individual time window, sufficient numbers of fringes (>25) were available to evaluate the Doppler frequency and minimize the error due to finite transit time broadening. Only Doppler bursts having SNR > 7.5 were considered for further analysis.

The flow temperature was obtained by analysing the corresponding phosphorescence bursts from individual time windows. Each phosphorescence burst (which represent optical signals from the 425–50 nm and 466–40 nm spectral regions, respectively) was time-integrated within its temporal full width at half maximum (FWHM). A single intensity ratios ($I_{425}/I_{466}$) was then computed for each acquired pair of burst and subsequently converted to temperature using calibration data obtained from the potential core of a temperature controlled jet.

In addition, using the raw Mie scattering signal, the number of bursts, $n$, and average transit times are evaluated in order to extract the proportion of time that a particle is present in the
measurement volume, which is then divided by the size of this volume according to the expression [11];

$$N = \frac{\sum_{i=1}^{n} t_i}{\pi w^2 L_e}$$ (1)

where \( t_i \) is the transit time of the individual burst signal, \( T_{RL} \) is the record duration of the acquisition, \( w \) is the radius of the beam at the measurement volume and, \( L_e \), is the effective length of the measurement volume.

2.5 Test case

Measurements were performed in a heated jet of air which is surrounded by a room temperature coflow of air, both seeded with 2 \( \mu \)m BAM:Eu\(^{2+} \) phosphor particles using in-house built magnetic stirrer particle seeders. The jet is electrically heated using temperature-controlled heaters (1245 W heating tape, Omega Engineering) wrapped around an extension of the central tube beneath the coflow chamber. The central tube conveying the heated air can easily be changed or removed and both gas streams in the tube and coflow can be operated independently of each other. Central tubes with a straight pipe profile (8 mm diameter) or a converging nozzle (5.5 mm diameter) were used in conjunction with an 80 mm diameter coflow tube. This central jet as well as the coflow configuration was mounted on a mill table, which can be translated in the x, y, and z directions relative to the fixed optical setup.

3. Investigation of potential cross-dependencies

3.1 Seeding density

At room temperature and under steady flow conditions with a flow velocity of 4 m/s, combined measurements were taken in the potential core of the seeded air jet to evaluate the seeding density and investigate any dependence on the measured temperature. Figure 4 shows the measured temperature as a function of seeding density. As seen here, the measured temperature does not change noticeably with seeding density. The error bars represent the statistical error of the mean temperature \((\sigma / \sqrt{n})\) estimated from the single-shot standard deviation \(\sigma\) and the number of bursts, \(n\), that were recorded in a measurement sequence. For a
fixed measurement duration, if there are more particles due to higher seeding densities, the average temperature is more accurate.

![Graph showing measured temperature as a function of seeding density.](image)

**Fig. 4** Measured temperature as a function of seeding density. The error bars represent the standard error of the mean temperature estimated from all the bursts, \( n \), in each measurement sequence \( \left( \sigma_{\text{temp}} / \sqrt{n} \right) \)

The seeding density suitable for the thermographic LDV technique is estimated to be in the range \( 10^{10} \sim 10^{11} \) particles/m³. Within this range, the number of acquired bursts which survives the previously-discussed 20 mV and LDV filtering criteria for evaluation of flow temperature and velocity is sufficient to provide a high data rate. At a seeding density of \( 5.9 \times 10^{10} \) particles per m³, the data rate of correlated temperature and velocity measurements is estimated as 1.2 kHz. This seeding density is slightly lower than that used in Thermographic PIV experiments of around \( 10^{11} \) particles/m³ [5].

Further tests were carried out to investigate the effect of seeding the coflow stream on the measured temperature in the central heated jet at 460 K. We observed that with or without seeding the 80 mm diameter coflow, the measured temperature was the same.

### 3.2 Laser Fluence

The laser fluence experienced by a particle depends on the time it spends traversing the probe volume, and therefore on its velocity. The fluence dependence on the velocity of the particle (flow velocity) can be expressed as:

\[
F = \frac{2P}{\pi W v_p} \quad (2)
\]
where $P$ (W) is the total emitted power of the laser, $w$ (cm) is the radius of the beam at the focus and $U_p$ (cm/s) is the velocity of the particle. The total emitted power given by definition above is restricted to the single UV beam and not the total emitted power in the three beams. By switching on and off the 514.5 nm beams, it was confirmed that the optical power from the two visible beams does not affect the measured temperature.

To investigate the presence and possible effects of a velocity-dependent laser fluence on measured flow temperature, measurements were taken by seeding BAM:Eu$^{2+}$ particles into a room temperature air flow, and then varying the flow rates over a range in order to change the velocity of the flow/particles in a central tube with a 5.5 mm diameter nozzle. To explore lower flow velocities, measurements were taken in the larger coflow.

![Figure 5](image.png)

**Fig. 5** Effects of flow velocity on measured flow temperature.

Figure 5 shows that the evaluated intensity ratio/temperature has a weak dependence on changes in particle velocity. Within the investigated range, for flow velocities in the range 0.1 m/s – 1 m/s, an estimated temperature difference of 10 K is observed, and beyond 1 m/s up to 13 m/s, a 5 K difference is observed. The overall temperature change of about 15 K estimated across the range of velocities here is suggests optical heating effects of the particle by the laser beam.

The utility of the equation 2 is further explored by varying the laser power at fixed flow velocity. Measurements in the seeded air flow at room temperature were taken a location 4 mm above the centreline of a 5.5 mm nozzle. At a fixed laser output power of 70 mW, the flow velocity was varied in a range 3.3 m/s – 10 m/s. Thereafter, the flow velocity was kept steady at 4.8 m/s, while the laser optical output power was varied in a range 20 mW- 70 mW (3.5 – 12.4 mJ/cm$^2$). The result from both experiments is shown in figure 6. An 8 K change in mean temperature is evaluated to occur for this range of estimated laser fluence. Within this range, the mean values of temperature
evaluated from the two different experiments (varying velocity and varying laser power) are in good agreement.

**Fig. 6** Laser fluence effects on temperature measurements by changing laser power and flow velocity, 3.3 m/s – 10 m/s. At each laser fluence, repeated measurements were taken and each data point represents the estimated temperature from a single acquisition.

**Fig. 7** Schematic of the cross-section in the x-y plane of the combined measurement volume and different probable vertical particle trajectories across the measurement volume. The time between successive particle crossings is random with an exponential probability distribution.

For the thermographic LDV technique, only a portion of the measurement volume formed at the intersection of the three laser beams, which defines our spatial resolution (150 µm x 150 µm x 250 µm) is being imaged onto the PMTs. Successive seeded particles will pass through various parts of the measurement volume that is finite by virtue of its diameter as shown in figure 7. For a fixed flow velocity, the maximum transit time of a particle crossing the beam will be observed when it crosses the beam centreline in the stream-wise direction. Therefore, an additional consideration is that across the measurement volume, each particle will be subjected to a laser fluence that varies proportionally with the local excitation intensity depending on its trajectory through the beam.
However, the fluence dependence as a whole is relatively weak. If necessary it can also be corrected for based on the simultaneously acquired flow velocity. For measurements in heated jet of air seeded with BAM:Eu$^{2+}$ as flow tracers, if the laser output power and flow conditions are known when performing the calibration, the velocity-dependent laser fluence will have a weak effect on the measurement accuracy in the actual measurements.

4. Measurements in a heated air jet

4.1 Accuracy of simultaneous point temperature measurements

To evaluate the accuracy of temperature measurements using the thermographic LDV technique, temperature and velocity (T-U) profile measurements were carried out at 4 mm (0.5D) above the 8 mm inner diameter straight circular tube with a coflow velocity of 0.1 m/s. Both streams was seeded with BAM:Eu$^{2+}$ particles. By translating the jet in the z-axis direction shown in figure 3, the thermographic LDV probe was used to make transverse exit temperature and velocity profiles measurements at radial positions across the heated air jet. Thermocouple measurements were taken in an alternating manner at the end of each acquisition of Doppler and phosphorescence bursts at a particular radial location. The velocity and temperature conditions during calibration are given in the table below. Over this range of velocities, the velocity dependence of the measured temperature does not have an effect.

<table>
<thead>
<tr>
<th>flow temperature (K)</th>
<th>flow velocity (m/s)</th>
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</thead>
<tbody>
<tr>
<td>295</td>
<td>5.1</td>
</tr>
<tr>
<td>334</td>
<td>5.8</td>
</tr>
<tr>
<td>402</td>
<td>6.9</td>
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<tr>
<td>522</td>
<td>8.6</td>
</tr>
<tr>
<td>541</td>
<td>9.3</td>
</tr>
</tbody>
</table>

Table.1: Flow conditions during calibration measured in the potential core of the heated jet using the thermographic LDV technique.

Figure 8(a) shows the simultaneous T-U profile measurements. As expected the profiles are well matched. Figure 8(b) shows the comparison of the point-based optical thermometry measurements with the thermocouple readings. The mean deviation is 7 K (1.8%). The deviation of the temperature measurements from the thermocouple measurements observed at radial
positions in the coflow where the flow velocity is < 1 m/s, may suggest the possibility of optical heating of the particle by the UV laser beam because the particle spends longer time traversing the measurement volume.

**Fig. 8** Transverse profile measurements taken at 0.5D from the jet exit of a 8 mm straight circular tube (a) mean TLDV (thermographic LDV) temperature and velocity measurements (b) TLDV (thermographic LDV) temperature measurements compared with thermocouple measurements.

### 4.2 T-U profile measurements in a heated jet with a converging nozzle

Temperature and velocity profile measurements were carried out at 8.5 mm (1.5D) above a heated air jet seeded with BAM:Eu²⁺ particles discharged into the ambient from a converging nozzle of 5.5 mm diameter fitted to a 8 mm straight circular tube. The coflow that surrounded the central nozzle was similarly seeded with BAM:Eu²⁺ particles. The flow velocity at room temperature was 7 m/s, giving a flow Reynolds number of approximately 2,600, and the coflow velocity was 0.1 m/s.

Here, by translating the combined flow configuration comprising of nozzle and coflow, the thermographic LDV probe was used to obtain a cross-stream T-U profile of both mean and fluctuating components of the temperature and velocity. Figure 9 shows the mean T-U profiles as well as their corresponding rms values. For each radial location, measurements were taken twice and the mean temperature deviation between the sets of measurement is 3.2 K (1%) with a maximum deviation of 9 K (2.8 %). The magnitude of the temperature fluctuations has not been fully established here partly due to lower precision of the thermographic LDV technique at 500 K (~ 35-40 K) [10]. The near top-hat profile of the velocity profile at this is cross-stream location (1.5D) is due to uniform velocity boundary condition imposed by the presence of the converging nozzle,
which will be more pronounced for profiles taken at jet exit locations < 1.5D above the nozzle. Since the uniform temperature boundary condition is not met at the mouth of the nozzle, a near Gaussian or narrower profile in the temperature is observed at this location, also observed in [12].

![Graphs](image)

**Fig. 9** Transverse profile measurements (top – mean values, bottom – rms values) taken at 1.5D from the jet exit of a 5.5 mm converging nozzle: (a) temperature measurements (b) velocity measurements.

### 5. Conclusions

Simultaneous point measurements of gas temperature and velocity was carried out using phosphor thermometry and a conventional LDV in an approach termed the thermographic laser Doppler velocimetry technique that is based on a single seeded tracer (BAM:Eu$^{2+}$). The influence of seeding density on flow temperature measurements is studied. As expected, higher seeding densities do not affect the measured temperature, while they permit combined vector-scalar measurements to be obtained at higher data rates with better-converged scalar statistical quantities. The effect of the velocity-dependent laser fluence was also investigated and a weak effect on temperature measurements was measured. As a particle traverses the measurement volume, it is exposed to an excitation fluence from the UV beam that is proportional to the inverse of its velocity through the beam. Temperature changes on the order 5 K were observed for flow velocities in the range 1 m/s – 13 m/s, with a marginally more prominent dependence at even lower flow velocities. It is usually possible to obtain accurate results by calibrating the technique in the regime of the flow velocities to be measured.
Transverse exit temperature and velocity profiles in a heated air jet seeded with BAM:Eu$^{2+}$ particles were measured to establish the accuracy of the temperature measurements and to demonstrate the utility of the thermographic LDV technique. This study demonstrates the utility of this point-based technique for vector-scalar measurements with a temperature accuracy of 2%. Future research will focus on improving the precision of the temperature measurement with the thermographic LDV technique by exploring other measurement strategies and phosphors that provide improved temperature sensitivity.

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References


