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OPTICAL THERMOMETRY COUPLED TO THE MEASUREMENT OF OTHER QUANTITIES (VELOCITY, PRESSURE)

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ABSTRACT

The visualization and quantification of thermal mixing in turbulent fluid flows is key to the development of accurate turbulence modelling. These models are needed to predict the behaviour of flows in industrially relevant applications as well as geophysical flows (ocean, atmosphere, earth's mantle, etc.). This talk will describe thermometry techniques based on luminescent tracer particles which can be combined with particle-based velocimetry to image both temperature and velocity in laboratory flows. The emphasis will be mostly on inorganic luminescent crystals, typically referred to as thermographic phosphors. These particles exhibit a wide range of luminescence properties and can be chosen to match the application needs, e.g., for use in cryogenic flows, at physiological temperatures, or up to 1000 K. There are also various implementations of this measurement concept. We can exploit the temperature dependence of the luminescence emission spectrum or the decay time of the particles to measure the temperature. The velocity can be measured simultaneously using temporally separated images of the particles using light scattering as in traditional Particle Image Velocimetry (PIV), using luminescence light or even single images of phosphorescence streaks caused by the motion of the particles during their luminescence decay.

Recent developments include high-resolution measurements in submillimeter boundary layers, a proof-of-concept study of 3D temperature and velocity measurements in gas flows, and 2D thermometry in water with sub-°C precision.

INTRODUCTION

The ubiquitous presence of thermometers in daily life is indicative of the significant influence temperature has on thermodynamical, thermomechanical and thermochemical variables. As examples, we can mention the diffusive properties of fluids, the chemical reactions rates, the saturation pressure of fluids or the solubility of gas such as oxygen in liquids. Common thermometers typically provide "absolute" temperature value, within a system: the human body, the oil in the pan or in a car engine, the water in the swimming pool because this value informs on the temperature-sensitive variables of interest, such as physiological activity, viscosity, decomposition rate. Properties are rarely insensitive to temperature, so a large part of temperature sensing applications are concerned with correcting the reading of other sensors, for example for pH, pressure, velocity, flow rates. In that case temperature accuracy is critical.

In fluid flow research, we are generally more interested in spatial or temporal derivatives of the temperature, which serve to detect the location and power density of heat sources, to estimate density variations resulting in buoyancy forces, or to quantify heat transfer. We can therefore tolerate larger error in the absolute temperature value that for the cases of the previous paragraph, as long as we can detect small relative temperature variations. Here we aim rather at achieving high spatial, temporal and temperature resolution (or precision), since they dictate together the uncertainty in spatial or temporal derivatives. Optical imaging techniques, can provide two- or sometimes three-dimensional information, and can rely on laser illumination to probe only a "thin" spatial or temporal slice of the flow.

Accurately predicting mass or heat transport in turbulent flows requires turbulence models with various levels of complexity. They necessitate calibration or validation step by "ground truth" reference data, either provided by direct numerical simulation (DNS) or experiments. As DNS is limited to low turbulent Reynolds number and/or small domain size, experiments remain necessary. An experimental data which would be crucial for turbulence model development are the so-called turbulent diffusion terms, which quantify the correlation between fluctuations of the velocity and

of a scalar quantity such as temperature, or concentration. Imaging of temperature alone is no longer sufficient, and velocity must be measured at the same location and at the same time. In this talk, we will cover optical techniques based on luminescent particles, which can act both as local thermometers and as flow tracers, therefore being able to provide correlated velocity and temperature information

PHOSPHOR PARTICLES

Phosphors are inorganic solid materials, which function is to convert light. They are generally in the form of polycrystalline ceramic particles. Note that most phosphors do not contain the element phosphorus, but phosphors and phosphorus share the property of luminescence, which is in their common greek root „phosphoros" – which means light bearer. Phosphor crystals are doped with luminescent ions, that means that a small fraction of the elements in the crystal are replaced with elements with specific electronic configurations. These dopants confer to the crystal its light absorbing and light converting properties. The light re-emission or luminescence, is as many physical processes sensitive to temperature. Unlike fluorescence, or phosphorescent molecules, the luminescence from phosphors is generally insensitive to the gas composition, in particular oxygen concentration and to the pressure. The ceramic nature of phosphors also provide their excellent thermochemical stability. Finally, various elements can be doped in a wide range of crystal phases, so that phosphor luminescent properties can be very varied, with emission from the UV to the mid-wave infrared, and temperature sensitive range which can be for example in the cryogenic range or around 1500 K.

Thermometry using these temperature sensitive particles, is refered to as phosphor thermometry. Often particles are applied onto a surface, using a binder material, to infer the surface temperature. This technique is often applied in combustion: on combustor wall, injector tip. It is then used to derive flame to wall heat transfer rates or to provide thermal boundary conditions for simulations of the fluid domain. However, there are also many other applications, e.g. to measure the surface of discharging batteries, that of rotating objects, or in biological media to name a few.

PHOSPHOR PARTICLES IN PRESSURE SENSITIVE PAINTS

As an example for the need of temperature measurements to correct another sensor, we mention here one of our recent study on pressure sensitive paints. These paints incorporate phosphorescent molecules, which emission can be extinguished by collision with oxygen molecules. When operating in wind tunnel with constant oxygen mole fraction, these paints which detect the oxygen partial pressure can be used as total static pressure measurements. Unfortunately, the luminescence is not only extinguished by oxygen molecules, but also by temperature. State of the art pressure sensitive paints, which are able to track pressure fluctuations at kHz rate over a wing model have very high temperature sensitivity on the order of 2%/°C, while their pressure sensitivity is below 1%/kPa. That means a variation of 1K in temperature, relates to at least a 2 kPa error. In wind tunnel experiments, the temperature continuously varies, sometimes by tens of degree, so that if not corrected for, temperature variations would lead to very wrong results. Correction is often done by integrating pressure taps to account for the temperature variations, but this is not possible for thin and/or rotating models. Since inorganic phosphors are insensitive to oxygen concentration, they can be integrated into a pressure sensitive paint to indicate the paint temperature without having to know the pressure. The temperature information can then be used to remove the contribution of the temperature variations on the pressure signal.

FLUID THERMOMETRY METHODS USING PHOSPHORS

To measure the fluid temperature, micron size particles are introduced into the flow. The approach relies on the assumption of thermal equilibrium between the fluid and the particle. Heat transfer for this size of particles is mainly by conduction. The particle thermal conductivity being large compared to that of the fluid, heat transfer is limited by thermal diffusion through the fluid and the particle temperature can be considered uniform. To derive temperature response times, we also consider that for gases, the thermal diffusivity of the fluid is high, leading to a very simple expression of a exponential decay response to a step-change variation in fluid temperature, with a time constant $\tau_T = {d_p}^2 \frac{\rho_p C_{pp}}{12 k_f}$.

Here d_p is the particle diameter, ρ_p the particle density, C_{pp} the particle heat capacity and k_f the thermal conductivity of the fluid. Phosphor particles are typically produced as micron size powder. Considering a 2 micron diameter particle, the thermal relaxation time constant is about 100 µs in air at 300 K. Across a flame front, the relaxation time constant gets significantly shorter, as the thermal conductivity increases.

The most obvious temperature sensitive response of luminescence sensors, is that of the emission intensity. Due to thermal quenching, when the temperature increases above a certain value (which greatly varies depending on the different dopant/host crystal phase combinations), the luminescence quenching rates become significant, which results in a drop in emission intensity. However this response cannot be exploited for reliable measurements, as the

detected signal intensity on a camera also scales with the particle concentration, and the distribution in excitation light. Those two quantities can vary significantly in time and space in a practical experiment due for example to light refraction at interfaces, or mixing of particle streams. Instead we exploit temporal or spectral variations of luminescence with temperature, to make the measurements independent of absolute light level. Either it is the persistence time or decay time of the luminescence after the end of the excitation, which is used as a measure of temperature, or the shift in emission spectrum or apparent colour.

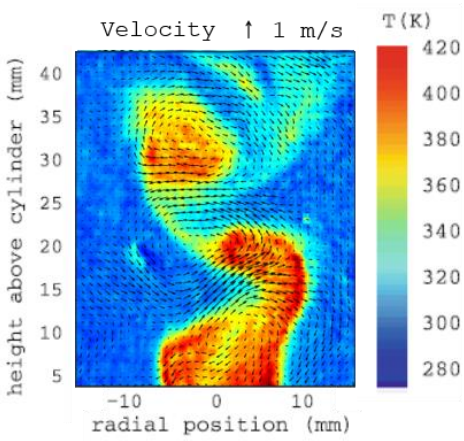

Fig. 1 Temperature and velocity field measured in the airflow in the wake of a heated cylinder [1]

To measure the velocity of the particles together with their temperature, we can simply exploit the shift in the particle position over time. In general we use lasers capable of delivery two shorts pulses of light during a short time, so that the particles only move by a few pixels between the two images. An example of combined temperature and velocity measurement obtained in the wake of a heated cylinder by this combined approach is shown in Fig. 1. Counter rotating eddies are alternatively shed from the cylinder on either side, and shear apart pockets of warm fluid which had formed near the rear stagnation point of the cylinder. This shearing process increase the surface area for heat exchange with the cooler surrounding fluid, leading to thin regions at intermediate temperatures between the two warm pockets.

While the spatial and temporal resolution is determined mainly by the laser and imaging system, the temperature range and temperature resolution is directly linked to the choice of phosphor and temperature sensitive response. We provide here two examples.

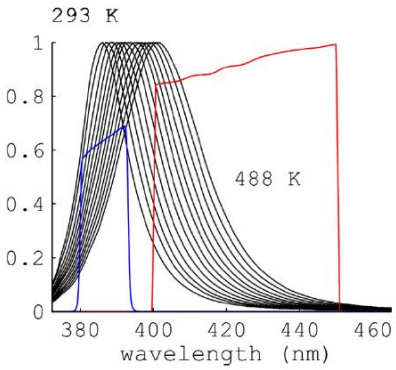

Fig. 2 ZnO emission spectrum and spectral filters [2]

The first is ZnO which can be used for a range of about 200 K with a precision in the order of 5 K. The range can start anywhere between 100 and 300 K. This depends on the choice of spectral filters used to detect with high sensitivity the change in emission colour. The ZnO emission spectrum in the range 20°C to 215°C is shown in Fig. 2. It is normalised to the emission maximum for each temperature. As the temperature increases, the emission band shifts towards higher wavelengths. Two filters are chosen, so that the area under the red curve increase with temperature and that area under the blue curve decreases. The ratio of the intensities collected by the two filters is therefore a monotonic function of temperature which can be calibrated against a reference sensor.

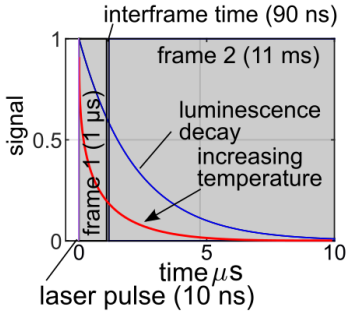

Fig. 3 Temporal diagram for rapid lifetime determination using a double frame camera and a pulse laser [3]

Instead of relying on emission spectrum changes, we can also image changes in the decay time. For this we can use a rapid lifetime determination approach with a double frame camera, as described in Fig. 3. Those cameras are able to take two exposure separated by only a short time delay (on the order of 100's of nanosecond), and are therefore used in PIV to capture the images of the particles during the two subsequent laser pulses. Here we place the excitation laser pulse during the first frame, so that the second exposure starts about 1 microsecond after the laser pulse. At the temperature increases, the decay time shortens so that the intensity collected by the second image relative to the first image is lower.

For this approach to work, the decay time of the phosphor needs to be sufficiently short, so that the particles do not move significantly during the second image, but also sufficiently long otherwise the second image is too late to detect any luminescence signal. An ideal range is 1-5 microseconds. For this approach to work, we need phoshors with decay time in that range, but that are also sensitive around the temperature of interest. Some phosphors such as $BaMgAl_{10}O_{17}:Eu^{2+}$, shows this behaviour but only at 500°C which is only of use to very specific applications. Many laboratory flows can study heat transfer around room temperature. We identified from some physics studies from the 70s, a material which has the right decay time and sensitivity. The composition is ScVO4:Bi, which has a short decay time of around 4 microseconds at 0°C and which rapidly changes with temperature around 20°C. The rate of change or temperature sensitivity is 2% per °C. We therefore synthesised, caracterised and applied this phosphor in a demonstration experiment shown in Fig. 4. Here the a cold liquid (30°C) is injected into a warm cuvette (50°C). Both hot and cold fluids are dispersion of water and phosphor particles. Based on a region unaffected by the jet, we can determine the temperature resolution of the approach as the standard deviation between pixels which are supposed to be at the same temperature. Here this single shot precision is 0.3 K.

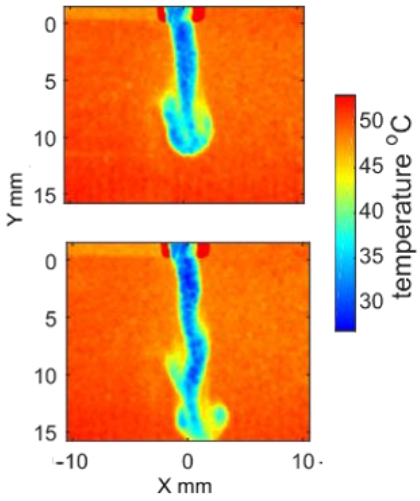

Fig. 4 Temperature fields in a water filled cuvette shortly after cold water injection [3]. Time separation (0.5 s)

3D MEASUREMENTS

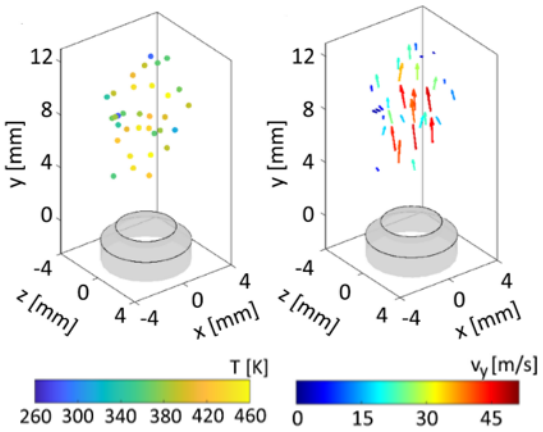

Fig. 5 Scatter plot of velocity and temperature data measured in a turbulent jet [4]

Using luminescent particle tracers, we showed that we can derive velocity and temperature information from the same particles. We can also exploit the fact the particles are distinct luminescence emitter in space, to make local temperature measurement in three dimensions. For this, we seed the particles in the flow, and take several views of the cameras to triangulate the position of each particle. We therefore imagined a system combining a 3D particle tracking velocimetry approach with a 2D two colour imaging approach. The 3D system determines the position of all the particles in the 3D space. The 2D two colour imaging approach capture luminescence particle image containing the temperature information for one view. If we isolate the signal from individual particles then the signal from that particle can be associated with its 3D position, and the ratio of luminescence intensity to its temperature. A demonstration of the concept is shown in Fig. 5, where one can see a scatter plot of velocity and temperature datapoints in the 3D space. Here particles are seeded in a turbulent heated jet surrounding by a coflowing stream. The aim is now to increase the density of temperature measurement using higher particle seeding concentration.

CONCLUSIONS

Luminescent particles make it possible to measure temperature and velocity simultaneously in a turbulent fluid flow using a single tracer. There are a variety of phosphors which can cover different temperature range, yet using the same instrumentation. The rapid lifetime system, which uses a single camera for temperature detection is particularly attractive for newcomers into the field.

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