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3D temperature and velocity measurements in microfluidics

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Abstract

In this contribution an optical measurement technique for simultaneous volumetric measurements of the temperature and the velocity fields in microfluidic channels is demonstrated. The temperature is obtained by evaluating the temperature sensitive luminescence signal of individual polymer particles doped with luminescent dyes, while the velocity field can be calculated simultaneously from the displacement of the individual particle images, if desired. The depth information is acquired, by means of astigmatism particle tracking velocimetry (APTV). With this method, the technique overcomes the measurement limitations associated with the depth of correlation and the spatial averaging in μPIV and μLIF.

1 Introduction

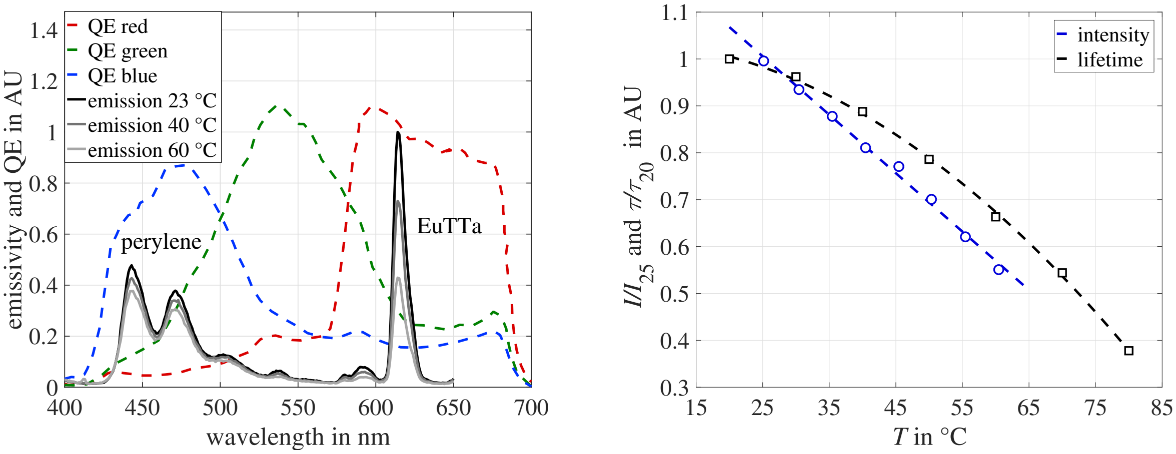
For a variety of microfluidic applications, simultaneous, volumetric and non-intrusive measurements of the temperature and the velocity fields are of high technical and scientific interest. Among others, the performance of microfluidic heat exchangers, microfluidic fuel cells and acoustofluidic micro mixers, is significantly influenced by both fields, which are often fully three-dimensional (Tullius et al., 2011; Faghri and Guo, 2005; Kiebert et al., 2017). Nevertheless, modern optical measurement methods such as particle image velocimetry, particle tracking velocimetry (PIV/PTV), particle image thermometry (PIT), laser induced fluorescence (LIF) or molecular tagging velocimetry and thermometry (MTV & T) are either purely two-dimensional or utilize multiple cameras to obtain the depth information (Kähler et al., 2016; Sakakibara and Adrian, 2004; Dabiri, 2009; Hu et al., 2010). However, due to the spatial restrictions and the limited optical access in microfluidics, multiple-camera techniques are difficult to implement. Furthermore, these restrictions lead to the use of volume illumination, since a thin light sheet is practically very challenging to realize. Thus, the measurement plane is not determined by the thickness of the laser light sheet as in macroscopic PIV, but by the depth of focus of the imaging optics. As a consequence, signals from outside of the focal plane are also imaged and significantly contribute to the cross correlation in PIV or accordingly to the fluorescence signal e.g. in LIF, causing a bias error of the measurement results if out of plane gradients are present (Cierpka and Kähler, 2012; Kim and Yoda, 2014). Similarly, the size of the interrogation windows imposes spatial averaging, which causes systematic errors in case of strong in-plane gradients (Kähler et al., 2012). These bias errors can be reduced by proper image preprocessing or by using smaller particles, however, these measures are limited and the systematic errors can only be fully avoided by utilizing three-dimensional particle tracking based measurement techniques (Rossi et al., 2012).

In order to overcome the aforementioned limitations, a method will be proposed and qualified in this contribution, that is capable of measuring the fully three-dimensional temperature and velocity fields in microfluidic channels with only one camera. The technique is based on the three-dimensional tracking of individual temperature sensitive luminescent polymer particles, thus enabling measurements without errors due to depth of correlation and window averaging.

2 Measurement technique

Polymethylmethacrylat (PMMA) particles doped with the luminescent dyes europium (III) thenoyltrifluoroacetonate (EuTTa) and perylene are used as tracers (Massing et al., 2016). The emission spectrum of the particles is depicted in fig. 1(a). The luminescent intensity and lifetime of EuTTa are strongly sensitive to temperature over a wide temperature range (see fig. 1(b)). Therefore, either the lifetime or the intensity of EuTTa can be measured and related to temperature by a calibration. The intensity based approach has the advantage of a simpler and cheaper measurement set-up, however, the luminescence intensity depends on the illumination intensity which can vary in time and space. Thus, an internal reference is needed, which is provided by the perylene signal in this case. Since the intensity of perylene is relatively insensitive to temperature (see fig. 1(a)), the ratio between the EuTTa and the perylene emission can be related to temperature without being affected by variations in the excitation light (Sakakibara and Adrian, 2004). This approach was successfully tested using two different cameras with the corresponding filters for both signals or a color camera (Massing et al., 2018). For lifetime based measurements, a reference signal is not necessary since the lifetime is an intrinsic property of the luminescent dye and therefore not altered by intensity artifacts, variations in the dye's concentration or photo bleaching. To resolve the lifetime, however, laser illumination in conjunction with a high speed camera and a complex synchronization is needed.

The three-dimensional position of the particles in the measurement volume is determined by the astigmatism particle tracking velocimetry (APTV) technique (Cierpka et al., 2010). In this method, astigmatic aberrations are induced by a cylindrical lens located between the camera and the primary imaging optics, which causes elliptical distortions of the particle images. The depth position of the particles can then be unambiguously determined from the length of the major axes of the elliptical particle images. Therefore, the x-y-z position of the particle can be determined via the X-Y position of the centroid in the camera image as in 2D PTV and the correlation of the elliptical shape of the particle images to their z-position. With this information, the 3D3C velocity field can be resolved by particle image tracking and the 3D temperature field can be determined simultaneously from the particle's luminescent intensity or lifetime. Both temperature measurement approaches were qualified experimentally via measurements in a temperature controlled microchannel and will be compared in the following sections with regard to their performance.



(a) Emission spectrum of EuTTa/perylene particles

(b) Temeprature response of the intensity and lifetime of EuTTa

Figure 1: a) Emission spectrum of EuTTa/perylene PMMA particles and quantum efficiency (QE) of a PCO Edge 5.5 sCMOS color camera. b) Normalized intensity and lifetime of EuTTa in PMMA as a function of temperature.

3 Experimental set-up and results

The experimental set-up used for the lifetime and the intensity based flow measurements is depicted in fig. 2. The investigated microchannel with a cross-section of 2×2 mm^2 and a length of 30 mm was milled into a solid copper block. The temperature of the block could be controlled with a thermostatic bath and was set

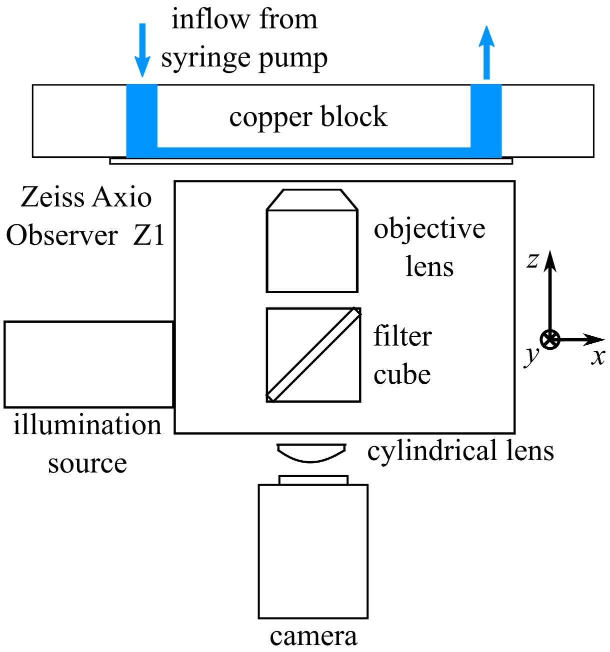


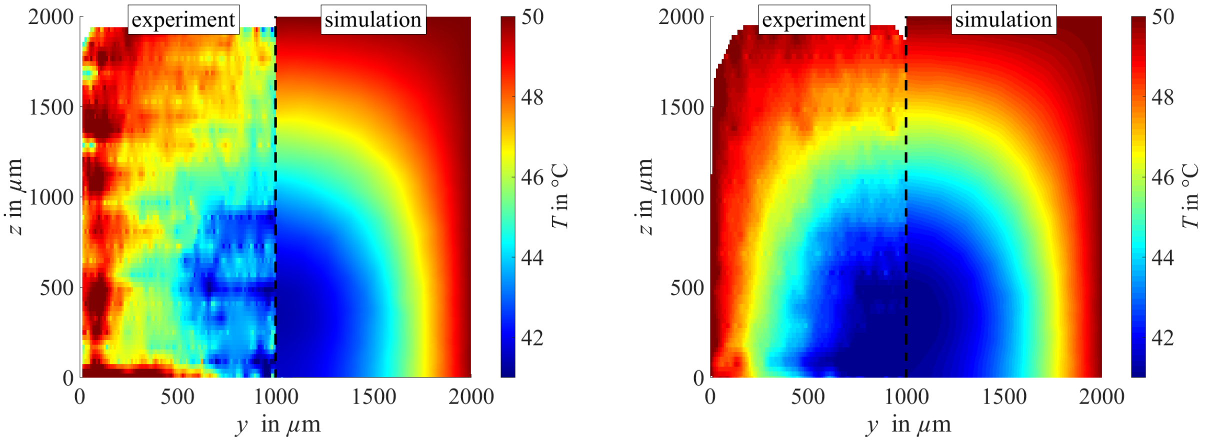
Figure 2: Schematic of the experimental set-up

to 50 °C, giving a constant temperature of the channel's copper walls during the experiment. The bottom wall consisted of a microscope slide to provide optical access. An aqueous 5 % NaCl solution was used as the working fluid and driven through the channel with a syringe pump with a constant volume flow rate of $\dot{V} = 1.1$ ml/min. The channel was observed with a Zeiss Axio Observer Z1 inverted microscope, which was equipped with a Zeiss EC Plan-Neofluar 10×/0.3 objective lens. Reflections of the illuminations light were filtered by a 405 nm dichroic mirror and a 420 nm long pass filter, which were placed in the microscope's filter cube. The astigmatism was induced by a cylindrical lens with a focal length of 850 mm, which resulted in a measurement volume depth of approx. $\Delta z \approx 130$ μm. To capture the channels entire cross section, 20 planes were scanned in depth direction with a distance of 100 μm.

For the intensity based approach the luminescence of the particles was excited with a Thorlabs Solis 365-C LED with a peak wavelength of 365 nm and imaged with a PCO edge 5.5 sCMOS color camera. The camera acquires color information via a Bayer filter. As can be seen in fig. 1(a) the emission of EuTTa is located within the the red channel of the camera, whereas the perylene emission is located within the blue channel. Thus, the signals can be separated by postprocessing and the intensity ratio can be determined with only one camera. For the lifetime based temperature estimation, a pulsed 355 nm Nd:Yag laser was used as the illumination source and images were captured with a PCO dimax HS4 high speed camera. To obtain the temperature, two images were captured during the luminescent decay and the temperature was calculated from the ratio of the signal intensity in the first and second image.

In fig. 3 and 4 the experimentally determined temperature and velocity fields in the cross section located 10 mm downstream of the channel inlet are compared to numerical simulations of the channel flow, which were performed with Fluent and serve as a benchmark solution. For the experimental data a spatial binning with a grid size of 10×25 μm^2 $(y \times z)$ was applied. Since the seeding concentration was low to avoid many overlapping particle images and the flow can be considered as steady, ensemble averaging over 500 recorded images was additionally applied.

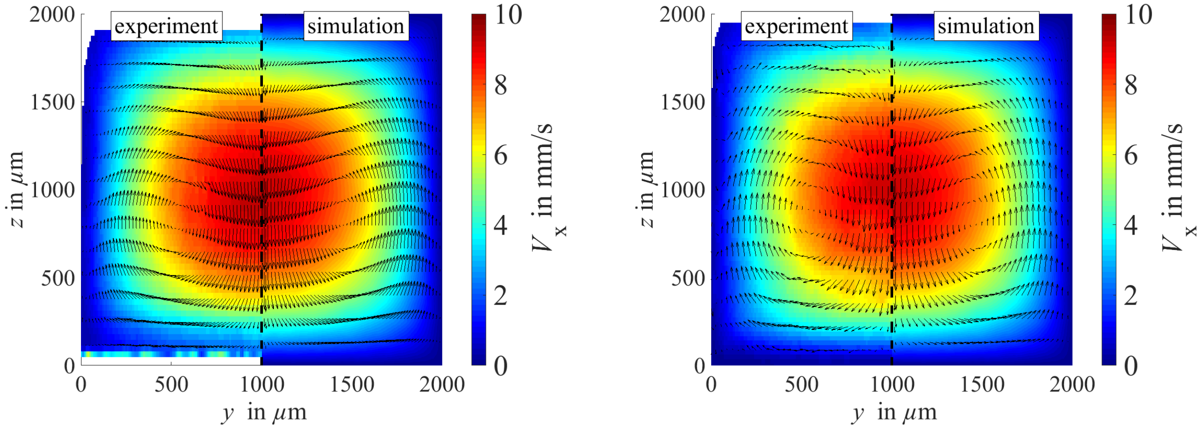
The minimum temperature in the channel center is approx. 41 °C (see fig. 3). The temperature increases toward the copper walls until the wall temperature is reached. The lower wall is modeled adiabatic, since the thermal conductivity of the copper walls is more than three orders of magnitude larger than for the acrylic glass bottom. Thus, the temperature gradient toward the channel bottom is $\partial T/\partial z = 0$ in the simulation. A good qualitative agreement between the measurement and the simulation can be observed in fig. 3 for both measurement methods. The temperature in the channel center and the temperature gradient toward the copper walls qualitatively corresponds between measurement and simulation. Furthermore, no significant temperature gradient at the bottom wall was measured, showing the validity of the adiabatic wall approximation for this experiment. Nevertheless, it can clearly be seen that the lifetime based measurement method performs better for temperature measurements in this configuration than the intensity based approach. The temperature fields measured with the color camera show a considerably higher scatter than the results of the lifetime based technique. It is evident, that the measurement uncertainty of the lifetime based approach is significantly smaller for the investigated temperature range. For the lifetime based technique the uncertainty is between ±0.29 °C to ±0.75 °C, whereas it is between ±0.4 °C to ±2.8 °C for the intensity based approach for a 95 % confidence interval. Furthermore, the temperature close to the wall deviates from the prescribed wall temperature by approx. 1 to 3 °C for the intensity based approach. These deviations can be attributed to reflections of the luminescent light at the highly reflective copper walls, causing bias errors. In the case of the lifetime based method, the measured wall temperature only deviates within the measurement uncertainty. Thus, this method is less affected by intensity artifacts due to reflections.



(a) Intensity based measurements

(b) Lifetime based measurements

Figure 3: Temperature field in the cross section measured 10 mm downstream of the channel inlet, determined with a) the intensity based method and b) the lifetime based method.



(a) Intensity based measurements

(b) Lifetime based measurements

Figure 4: Velocity field in the cross section measured 10 mm downstream of the channel inlet, determined with a) the intensity based method and b) the lifetime based method.

The simultaneously measured three components of the three-dimensional velocity field are presented in fig. 4. Both techniques give a good quantitative agreement between the measurement and the simulation for all three velocity components. In the main flow direction the typical velocity profile with the maximum in the center can be seen in the color map. The temperature induced density gradients cause an a secondary flow directed upward at both heated vertical walls. Because of continuity, this produces an inward directed flow in the top half of the channel, a downward directed flow in the channel center and an outward directed flow in the bottom half of the channel. Thus, two symmetrical, counter rotating vortices form in the channel with their center of circulation below the central horizontal axis at approx. $z = 850$ mm. This matches the results of Cheng and Hwang (1969) for a square channel with a constant, uniform temperature of all four channel walls. The velocity magnitude of the secondary flow is in the current case 0.35 mm/s and thus only approx. 3.5 % of the maximum velocity in flow direction. For both measurement methods, the measurement uncertainty is within 2 % of the maximum velocity for the velocities in main flow direction and in spanwise direction (V_x and V_y). At the same time the depth position of the particles in the measurement volume can be determined with μm accuracy. Thus, highly resolved and accurate measurements of the volumetric velocity field can be performed with both measurement approaches.

4 Conclusion

In this contribution a novel measurement technique was demonstrated, which combines the APTV method with single particle intensity based and lifetime based temperature determination for simultaneous, volumetric, single-camera measurements of the temperature and velocity fields in microfluidic applications. Measurement results in a heated microchannel show a significantly smaller temperature measurement uncertainty for the lifetime based approach than for the intensity based approach, whereas the velocity field could be measured with similar accuracy with both methods. Furthermore, the lifetime based approach was less affected by intensity artifacts due to reflections at the wall. Thus, it can be concluded, that for most microfluidic applications the lifetime based approach is preferable to the intensity based method at the current state of the techniques. However, it has to be acknowledged, that the experimental set-up for lifetime measurements is much more complex and expansive than for intensity based measurements.

Future improvements of the technique, especially with regard to the uncertainty for the temperature estimation, can be expected due to new hardware developments (e.g. stronger light sources, more sensitive cameras). Furthermore, the field of particle synthesis leaves much room for progress. For example, new luminescent complexes with more than two times higher temperature sensitivities than EuTTa have recently been developed (Ondrus et al., 2015). Doping appropriate polymer particles with these dyes will substantially reduce the measurement uncertainty of both methods, thus further increasing the impact of the technique.

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