Fachtagung "Lasermethoden in der Strömungsmesstechnik"
3. – 5. September 2013, München

Simultane Druck- und Geschwindigkeitsmessungen mittels lumineszierender Polystyren Mikrosphären

Simultaneous velocity and pressure measurements using ratio-metric luminescence of multi-dye microbeads

J. Massing[1], D. Lacroix[2], C. Cierpka[3], G.-S. Li[2], D. Dabiri[2], G.Khalil[2], C.J. Kähler[3]

[1] Department of Aeronautics and Astronautics, Technische Universitaet Berlin, Berlin 10623, Germany
[2] Department of Aeronautics and Astronautics, University of Washington, Seattle, Washington 98105, USA
[3] Institute for Fluid Dynamics and Aerodynamics, Bundeswehr University Munich, 85577 Neubiberg, Germany

Schlagworte: Drucksensitive Partikel, Druckfeldmessung, Particle Image Messmethode
Key words: Pressure Sensitive Particles, Pressurefield Measurement, Particle Image Method

Abstract

The use of luminescent dyes to measure 2-dimensional pressure and temperature fields is a common experimental procedure. Particle production methods have advanced to a point where particles can be doped or coated with one or more of these dyes. These polystyrene or silica based particles can be used to seed a fluid and determine the pressure or temperature field. Simultaneously, the velocity field can be calculated using particle image velocimetry (PIV). The practicability of simultaneous velocity and pressure measurements was already confirmed by Kimura et al. 2010 using measurement of phosphorescent lifetime for pressure calculation. In this contribution, the feasibility of an intensity-based method for pressure measurement will be investigated. Luminescent intensity of polystyrene microbeads doped with pressure-sensitive dyes, temperature-sensitive dyes and pressure- and temperature-insensitive dyes will be measured using methods similar to standard PIV techniques. It will be shown, that the intensity-based approach is applicable to simultaneous pressure and velocity measurements.

Introduction

Experimental methods that use optical measurement techniques, such as Digital Particle Image Velocimetry (DPIV) and Pressure- and Temperature-Sensitive Paint (PSP/TSP), are well-established and commonly used in various fields of research. They represent major advances over previous single-point measurement practices as described in Kutz 2013.
DPIV allows for simultaneous 2 – Dimensional velocity measurement in unsteady flows. The investigated flow is seeded with tracer beads that follow the flow's velocity. Upon illumination with a pulsed light source, two sequential images of the bead's trajectories are obtained using a charged coupled device (CCD). The velocity distribution can then be estimated through the bead displacements and the elapsed time between two succeeding images.

PSP provides a technique for continuous and non-intrusive global mapping of pressure distributions over aerodynamically loaded surfaces. The paint luminesces when excited by a light source, typically a laser. The intensity of the emitted light depends inversely proportional on the partial pressure of oxygen. This process is called oxygen quenching and is described in detail in Kutz 2013. Since the partial pressure of oxygen can be directly related to a pressure value by Henry's law, the intensity values can be used as a measurement for pressure. Details and applications of this methodology can be found in Kutz 2013.
Similarly to PSP, TSP can be applied to surfaces to measure temperature distribution. The intensity of the emitted light is inversely proportional to temperature, due to thermal quenching. Over certain temperature ranges it is possible to find a relation between temperature and luminescent intensity. This effect is described in detail in Liu et al. 2005.
These three techniques can be combined, by doping microbeads with pressure and temperature sensitive paint. With these so-called pressure- and temperature sensitive microbeads (PTSBeads) the pressure and temperature in the investigated flow region could be related to the emitted light. Kimura et al. 2010 showed the validity of this concept, by simultaneously measuring velocity and pressure in a small test chamber. The pressure distribution was determined by the lifetime measurement method, which is described in detail in Kimura et al. 2010.
In this paper, a similar experiment will be performed to measure the pressure distribution in a small chamber. Here, however, in contrast to the method used by Kimura et al. 2010, the intensity and not the lifetime of the emitted light will be used to obtain pressure. This technique however, requires the intensity variations due to pressure to be compared against a reference intensity that is insensitive to pressure variations. The settings and excitation conditions during the measurements must not vary significantly, which cannot be ensured during PIV measurements, due to bead movement. This makes microbeads that are only doped with PSP dyes insufficient for intensity based measurements. For this reason an additional fluorescent dye, which is insensitive to pressure and temperature changes, is introduced into the microbeads and serves as a reference. The emitted light from each dye has its own unique wavelength and is captured on separate cameras. The ratio of both images is related to pressure, to compensate for the described uncertainties. The microbeads used during this experiment are AEH - polystyrene microbeads loaded with Pt(II) octaethylporphine as the pressure-sensitive dye, Eu(III) thenoyltrifluoracetonate as the temperature-sensitive dye and Coumarin 500 as the reference dye. The maximum emission wavelength is around 650 nm for Pt(II) octaethylporphine, 615nm for Eu(III) thenoyltrifluoracetonate and 530 nm for Coumarin 500. Further details can be found in Cun et al. 2013.
The paper will show the feasibility of the intensity ratio approach, as well as its applicability in conjunction with particle image velocimetry.

Experimental Method

Two different approaches are used to measure pressure variation with pressure-sensitive polystyrene microbeads. The first approach is to measure the intensity values of microbeads spread on a microscope slide with a spectrometer. This will show that the intensity ratio method is feasible for measuring the expected intensity change over a certain pressure range. In the second approach, we measure the variation in intensity values of aerosolized floating microbeads, with respect to the surrounding pressure. This experiment will show the behavior of the particles in an environment, that is similar to future experimental set ups in a wind tunnel, and it will also prove that the intensity ratio method can be combined with PIV.

Spectrometer Set Up

The testing utilizing the spectrometer readings of wavelength and intensity is conducted in two primary phases. The first phase, shown in Figure 1, involves using a sealed chamber with a glass window, attached to a vacuum pump. Additionally, a pressure transducer, which is joined to the chamber, outputs voltages to Signal Express LabView through a National Instruments data acquisition board (BNC-2120). A sample of PTSbeads is painted onto a small glass slide and then positioned inside the vacuum chamber with the PTSbeads facing out the glass window. A 405 nm wavelength LED directed at the sample excites the PTSbeads, whose emitted light is captured by a miniature fiber optic spectrometer (USB4000, Ocean Optics, Dunedin, FL), and in turn, processed through the Spectrasuite Spectroscopy Software (Ocean Optics, Dunedin, FL). The second phase of the spectrometer testing, involves replacing the combination of the vacuum chamber and the vacuum pump with the primary test chamber of the experiment, described in detail in the following section. The slide sample of PTSbeads is secured in the testing chamber, illuminated by the 405 nm LED. Again, the emitted light from the PTSbeads is captured by the spectrometer.

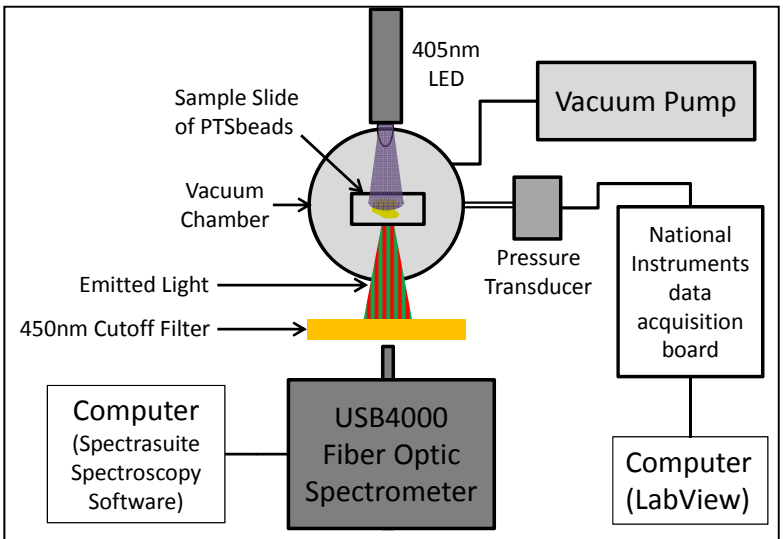

Figure 1 Schematic of spectrometer test (phase 1) set up with slide in the vacuum chamber (top view)

Floating Microbeads Set Up

The experimental set up within which the primary experiment was conducted is shown in Figure 2. The experiment is carried out inside a 35cm x 5cm x 5cm aluminum syringe chamber, to control the experimental environment (e.g. pressure). The control volume, which contains the PTSbeads sample, measures 6cm x 4cm x 4cm. A cylindrical opening with a diameter of 2.5 cm and a length of 12 cm was cut into the block. It holds a 60 ml syringe plunger, which is pulled out or pushed in to alter the pressure inside the chamber. To perform optical measurements, the chamber has a 6 cm x 2.5 cm opening on the top, the front and the bottom. A Barksdale 402h2 Series pressure transducer with a pressure range of 0-50 psi and an accuracy of 0.25% is used to monitor the pressure throughout the experiment. The signal of the transducer is sent to a Barksdale pressure sensor signal conditioner and monitored with a digital multimeter. Since the signal conditioner is adapted for the used pressure transducer, it is not necessary to perform a calibration before each experiment. The movement of the syringe plug is precisely controlled via a Harvard Apparatus compact infusion pump. Therefore small pressure changes can be generated in the chamber, which are solely limited by the accuracy of the pressure transducer. The ability of the chamber to hold pressure was verified by increasing and decreasing the pressure to the maximum and minimum level (1.5 and 0.7 bar) and monitoring the pressure for a period of 1 minute.

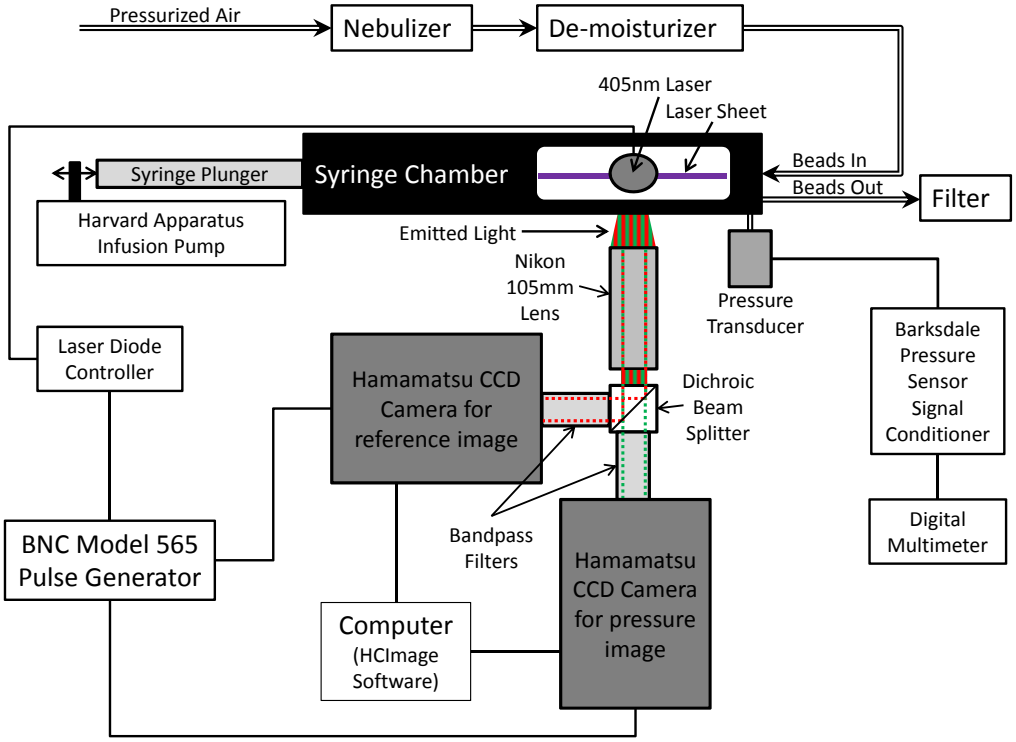

Figure 2 Scheme of floating microbeads experimental set up (top view)

A pulsed 405 nm wavelength laser diode is used as an excitation source with a pulse rate of 10 µs and output energy of 70 mW. The laser beam in conjunction with cylindrical lenses creates a 2-dimensional sheet of light that passes through the top window parallel to the length axis of the chamber.

Simultaneous images of the intensity values of the pressure and the reference dye are acquired using two Hamamatsu charged-coupled device (CCD) cameras (model C9100-13, Hamamatsu Photonics K. K., Japan), operated by the Hamamatsu HCImage software. The exposure time is set to the minimum of 30.53 ms. No binning and the fastest scan mode is used, which results in a readout time of 32 ms.

The cameras are arranged in front of the front window, orthogonally to the laser sheet and to each other. A BNC model 565 pulse generator is used as a pulse generator for the laser diode and to synchronize the cameras with the laser. The emitted light is split into two perpendicular beams with a dichroic beam splitter. A bandpass filter is attached to the front of each camera, allowing only the wavelength of the pressure or reference dye's luminescent light to pass. The filter on the reference camera is an Edmund Optics 527nm fluorescence bandpass with a 20nm bandpass while the filter on the pressure camera is a 655nm fluorescence bandpass with a 40nm bandpass. The cameras are used in conjunction with a Nikon 105mm lens, resulting in a field of view that is 2 x 2 cm².

Data Acquisition during Spectrometer Test

The vacuum chamber is used to obtain the intensity changes of the pressure dye with low pressures, where the intensity and signal-to-noise ratios are the greatest. The spectrometer data are recorded at atmospheric, 100 kPa , and then down to 2 kPa in increments of 20 kPa using the vacuum pump. For the second phase, the pressure in the primary testing chamber is decreased using a syringe pump from atmospheric to 70 kPa, in increments of 10 kPa. Finally, the second phase also involves increasing the pressure in this chamber from atmospheric to 160 kPa, again in increments of 10 kPa. The chamber tests are conducted to determine the range of pressure intensities associated with this setup and to compare with the higher intensities from the low range of pressure changes (from the vacuum pump). The

intensity values determined are the peak values from the spectrometer readings at the appropriate wavelengths for the pressure (650 nm) and reference (550 nm). The intensity results are normalized with respect to the atmospheric intensities captured at each phase. Therefore, the sets of normalized data can be appropriately compared.
The intensity ratio of the emitted light ($R=I_p/I_{ref}$) is calculated from the spectrum captured with the spectrometer. The maximum intensity values at the respective wavelength of the reference (530 nm) and pressure dye (630nm) are extracted, by applying a moving weighted average to the data. To approximate the experimental data, a fit with the sum of two exponential decays is used.

Data Acquisition with Floating Microbeads

During the floating microbeads test, the PTSbeads are aerosolized by a medical nebulizer and pumped into the chamber with pressurized air. When the maximum possible density of microbeads inside the syringe is reached, the chamber is sealed by closing the inlet and outlet valves. After pumping the microbeads in and sealing the chamber, the microbeads have to be allowed a time of approximately 10 seconds to stop moving and settle in a floating state, in order to avoid significant streaking.
The chamber is sealed at atmospheric pressure and a number of 50 images are taken. The plug is moved in, until the next pressure step is reached and another 50 images are taken. This procedure is repeated until the maximum pressure of 1.3 bar is reached. With the syringe plug pushed inside the valves are opened, restoring atmospheric pressure in the chamber. Now the plug is pulled out and at each pressure step from 1bar – 0.7bar 50 images are captured, resulting in an overall number of 350 images.
After every test, 50 background images are taken at the particular sensitivity gain and gain settings, which can be subtracted from the data images to account for noise. The obtained images are divided into smaller interrogation windows and an intensity ratio ($R=I_p/I_{ref}$) is calculated for each window. I_p and I_{ref} are defined as the arithmetic mean of the intensity values in each interrogation window for the pressure and reference image. This results in a mean intensity ratio for each interrogation window and therefore the spatial resolution depends on the window size. For each image the mean ratio is calculated using the arithmetic mean of the ratio in each interrogation window.

Results and Discussion

Figure 3 shows the intensity ratio of the pressure and reference dye over changing pressure, normalized with the ratio of atmospheric pressure. The data shows that the decay is strictly non-linear with a much higher resolution in the low pressure region. A similar behavior was already shown by Kimura 2010, which confirms that the intensity ratio method is feasible for capturing pressure changes.
Intensity measurements of airborne microbeads were obtained using a two camera system. In this approach, each of the cameras simultaneously captured the pressure-sensitive bead and the reference bead images. The particles were subjected to a pressure range of 0.7-1.3 bar and 50 images were taken at each pressure step of 0.1 bar. The intensity ratio for each pressure was calculated as described.
Several studies were performed in order to reduce the standard deviation of the ratios

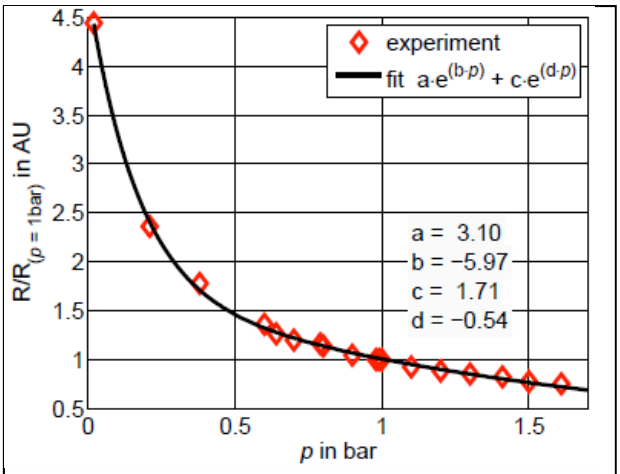

Figure 3 Normalized ratios of emission intensity of the pressure and reference-dye for varying pressure from spectrometer tests

at each pressure. The first of such studies involved processing the data with varying threshold intensities in the raw images (pixels below the threshold are ignored in interrogation window intensity averages). The interrogation windows were 16x16 pixels. The study presented processing threshold intensities corresponding to minimum standard deviations. The minimum standard deviation thresholds plotted against pressure showed a similar trend to the pre-processed reference image average intensity, showing that the usable threshold intensities can be determined based on the raw reference images. To further reduce the standard deviations, the same study was also performed on the pressure images' threshold.

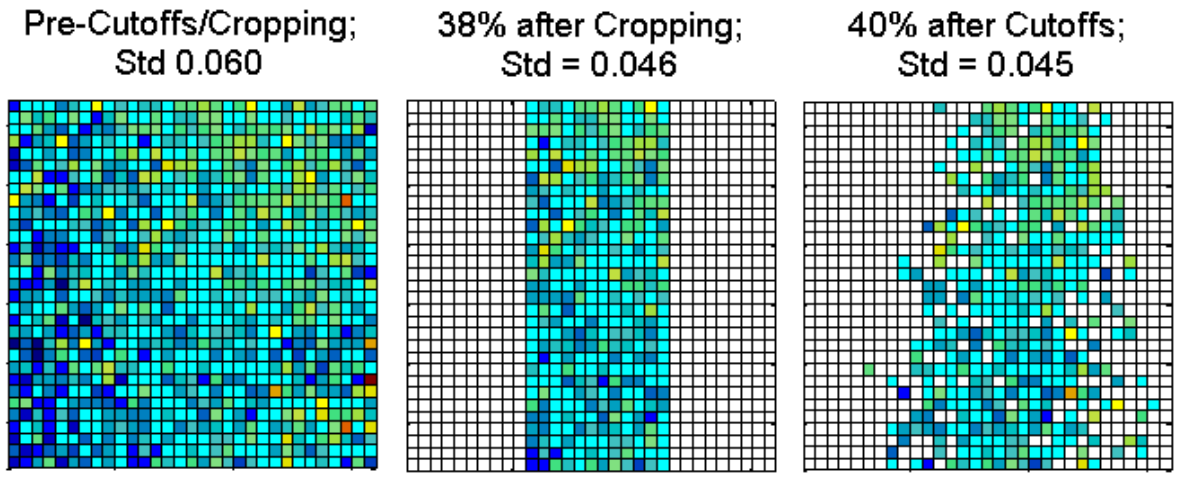

Figure 4 Example of ratios for an image pair at 90kPa without any cutoffs (left), with side cropping (middle), and with intensity and pixel percentage cutoffs (right).

Though this reduced the standard deviations, two additional investigations were performed to further reduce uncertainties. First, one third of the images were cropped on both sides, to eliminate the dark regions. This reduced the standard deviation from 0.06 to 0.045 (See Figure 4, middle). Second, a detailed analysis of the distribution of ratios per interrogation window (also 16 x 16 pixels) was performed. It was found that the interrogation windows resulting in outlier ratios had low average intensities in either the reference or pressure images, or they had significantly larger number of pixels that were dropped when processing due to thresholding, both of these resulted in larger uncertainties. To account for these, an analysis of various cutoffs was performed. First, an intensity cutoff was varied so that interrogation windows with average intensities below the cutoff were ignored. Second, a second cutoff eliminated ratios where the averages were calculated with less than a prescribed percentage of pixels/window. The final values for these cutoffs were determined based on what cutoff values would serve best to reduce those erroneous ratios. An example of this cutoff study is shown in Figure 4 (right).

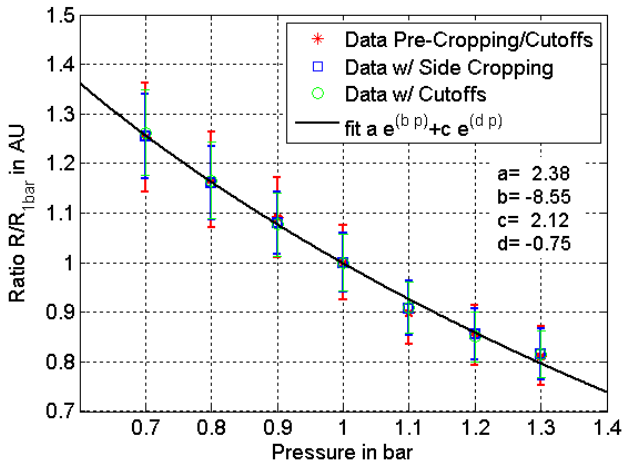

Figure 5 Normalized mean ratios of emission intensity of the pressure and reference dye over varying pressure for floating microbeads, interrogation window 16 x 16 pixels

Figure 5 shows the mean intensity ratio

normalized at 1 bar, for an interrogation window size of 16 x 16 pixels. The average ratio per image and standard deviation are also averaged over 50 images per pressure, and then plotted. The improved standard deviations now ranges from 5.6% at the higher pressures, to 6.8% at the lower pressures (16 x 16 interrogation windows).
The mean ratios and standard deviation were also calculated for different interrogation window sizes. Table 1 shows that the standard deviation increases with decreasing interrogation window size. Kimura et al. (2010) showed a standard deviation of <10% was acceptable, which can be obtained with a 16 x 16 pixels interrogation window size.

Table 1 Standard Deviation in percent for different interrogation windows

	8 x 8 pixels	16 x 16 pixels	32 x 32 pixels	64 x 64 pixels
Pre-Thresholds	20.8 %	9.3 %	6.3%	5.6 %
Pre-Cropping / Cutoffs	15.8%	7.6%	4.5%	3.5%
Side Cropping	12.7%	6.2%	3.5%	2.6%
Cutoffs	11.8%	6.1%	3.6%	2.7%

Conclusion and Future Work

The intensity ratio method has been investigated regarding it's feasibility for simultaneous velocity and pressure measurements using microbeads doped with a pressure-sensitive dye, a temperature sensitive dye and a pressure and temperature insensitive reference dye (PTSbeads).
A spectrometer was used for intensity measurements of stationary PTSbeads. The results showed the expected exponential decay in intensity ratio with increasing pressure due to oxygen quenching.
Intensity measurements for PTSbeads floating in an experimental chamber were done using two CCD-Cameras with a spatial resolution of 512 x 512 pixels. The pressure in the chamber was varied and 50 images were taken and processed for different pressures, which were constant in the chamber and thus in the entire field of view. Similar to PIV post processing, the image was split in smaller interrogation windows to calculate the average intensity ratio of the entire field of view. For interrogation windows of 16 x 16 pixels, the data showed a similar decay in intensity ratio as the spectrometer test. The spectrometer test and the floating microbeads test showed the feasibility of the intensity ratio approach for pressure measurements with PTSBeads.
The error was determined by the standard deviation of the intensity ratios and was an average of 9.3% for an interrogation window size of 16 x 16 pixels. It was shown, that the error is highly dependent on interrogation window size. Low signal-to-noise ratio, and low pixel use were also determined to be sources of error. Additional post-processing methods showed that the standard deviation can also be reduced by side cropping, or intensity and pixel percentage cutoffs, though the latter is preferable. Overall, the average standard deviation for the 16 x 16 interrogation windows dropped by 34.4%, from 9.3% to 6.1%. Similar improvements can also be seen in the other sizes of interrogation windows.

Acknowledgements

This work is the product of collaborative interactions between C.J. Kähler's group at the Bundeswehr University (Munich, Germany), and D. Dabiri's group at the University of Washington (Seattle, WA, USA). This work is supported by the National Science Foundation

Grant No. 05177821 in the USA and German Research Foundation under the individual grants program KA 1808/8 in Germany.

Reference

Hamamatsu Photonics, 2006: EM-CCD Technical note. Hamamatsu, Japan

Im SH, Khalil G, Callis J, Ahn BH, Xia Y, 2005: Synthesis of polystyrene beads loaded with dual luminophors for self referenced oxygen sensing. Talanta 67:492–497

Kimura F, McCann J, Khalil GE, Dabiri D, Xia Y, Callis JB, 2010: Simultaneous velocity and pressure measurements using luminescent microspheres. Rev Sci Instrum 81:064101, DOI 10.1063/1.3422324

Kutz M, 2013: Handbook of measurement in science and engineering. Wiley, Hoboken, New Jersey, USA

Liu T, Sullivan JP, 2005: Pressure and temperature sensitive paints. Springer, New York, USA

Zhu C, Deng R, Khalil GE, Dabiri D, Gu Z, Xia Y, 2013: Synthesis and Characterization of Pressure and Temperature Dual-responsive Polystyrene Microbeads. Particle & Particle Systems Characterization 30:542–548