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LETTER

Inexpensive fluorescent particles for large-scale experiments using particle image velocimetry

Francisco Pedocchi · J. Ezequiel Martin · Marcelo H. García

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Abstract Custom-produced fluorescent particles are presented and their use as tracers for particle image velocimetry is evaluated. The fabrication procedure is explained and the main properties of the particles are described. The advantages of using fluorescent particles over nonfluorescent ones are discussed, in particular, for applications involving large facilities, as those used in hydraulic research. Images using the produced particles are also shown.

1 Introduction

The use of particle image velocimetry (PIV) has expanded in the last decade with the popularization and improvement of digital cameras and the increase in computational capacity that allows for faster analysis of the large amounts of data involved in this technique. The hydraulics research community has not been indifferent to this trend and PIV is now a well-established technique in the study of environmental flows, with water flow in open channels probably the simplest example of these flows.

In hydraulic research, the size of the experiments tends to be larger than those used in other areas of engineering and physics. Additionally, the presence of free surfaces, interfaces and suspended sediments is common in hydraulic applications. All these characteristics tend to introduce undesired sources of reflection that reduce the quality of the measurements that may be obtained. In some cases, reflections can make measurements nearly impossible using standard PIV techniques, as in the case of measurements close to a sandy sediment bed or close to the free water surface (Admiraal et al. 2006; Bigillon et al. 2006).

The use of fluorescent particles reduces the effect of these undesired reflections. Fluorescent molecules have an absorption spectrum that differs from their emission spectrum, effectively shifting the wavelength of the incident light. In this way, the monochrome emission of a laser illuminating the particles is captured at a different wavelength, while reflections can be filtered. For example, if a Nd:YAG laser is used (532 nm, green) to illuminate Rhodamine WT, the emission from the molecules occurs in the yellow–red wavelengths. Then, by using a bandpass filter, any undesired green light reflection is eliminated and only the signal from the fluorescent molecules contained in the particles is recorded. Unfortunately, the cost of the commercially available fluorescent particles (in the order of US $2,000 for a 100 g bottle) limits their utilization to small-scale experiments and those for which particles can be reused. In facilities containing thousands of liters of water like those frequently used for hydraulic research, the cost of commercial fluorescent particles can be prohibiting.

The aforementioned situation motivated the development of an inexpensive way of producing fluorescent particles that can be used for PIV measurements. The

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F. Pedocchi (✉) · J. E. Martin · M. H. García
Ven Te Chow Hydrosystems Laboratory, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N. Mathews Ave., Urbana, IL 61801, USA
e-mail: pedocchi@uiuc.edu

J. E. Martin
e-mail: jemartn1@uiuc.edu

M. H. García
e-mail: mhgarcia@uiuc.edu

estimated cost of producing these particles is in the order of US $50 per 100 g. These particles have been successfully used by Martin et al. (2006) to perform measurements in stratified flows. This article serves as a way to share with the rest of the research community the method of fabrication that we have developed, expecting that it can facilitate the work of researchers dealing with large-size experiments.

2 Particle description

An effective method to produce fluorescent particles is mixing the fluorescent dye within the material used to form the particles. The selected fluorescent dye was Rhodamine WT for its low toxicity (Rhodamine WT is commonly used as a tracer in environmental studies); its absorption and emission spectra are presented in Fig. 1 [adapted from Wilson et al. (1986)]. Other available fluorescent tracers have been evaluated by Rottenkolber et al. (2000). An aqueous solution of Rhodamine WT at 20% concentration in volume was mixed with commercial grade liquid polyester resin, regularly used in fiberglass casting. The final concentration by volume of Rhodamine WT was approximately 0.1%. This concentration was found to provide adequate particle images, while minimizing the amount of dye required. The resin was then processed following the manufacturer instructions to form a solid block. The plastic block was ground and the powder obtained was then sieved, retaining only the finer fraction for use as a tracer. The smallest sieve used was a No. 230 mesh, corresponding to particles of size 63 µm and finer.

A laser diffraction particle sizer, the LISST-ST, produced by Sequoia Inc., was used to measure the settling velocity and size distribution of the selected particle fraction. The instrument reports cross section concentration evolution for eight logarithmically distributed sizes between 1.74 and 179.53 µm during a 22-h settling experiment. From these records, the concentration and the settling velocities were computed following the procedure described by Pedocchi and García (2006). The cross section concentration measured by the LISST-ST was divided by the square of the mean diameter in each size class to yield the relative number of particles for each size class (Fig. 2). The settling velocities were only computed for the size classes that presented significant concentrations (Fig. 3). Stokes' law for settling velocity of small particles

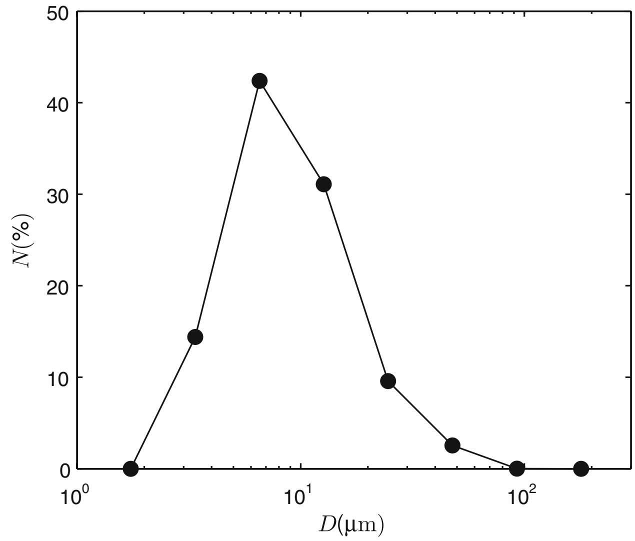

Fig. 2 Particle size distribution as percentage of the number of particles in each size class compared to the total number of particles

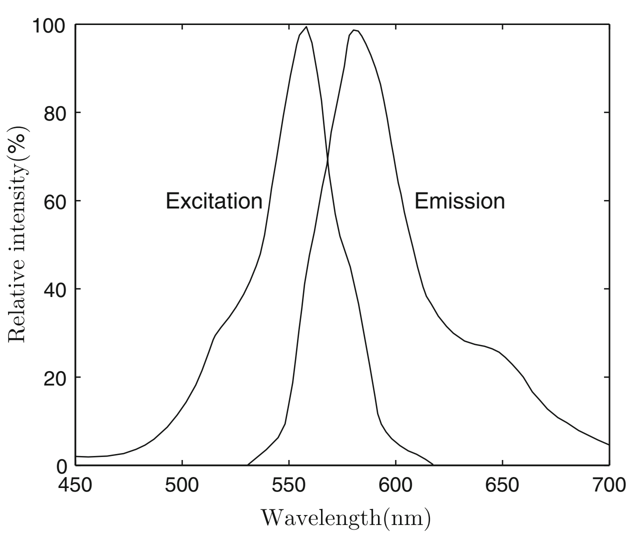

Fig. 1 Excitation and emission spectra of the Rhodamine WT (after Wilson et al. 1986)

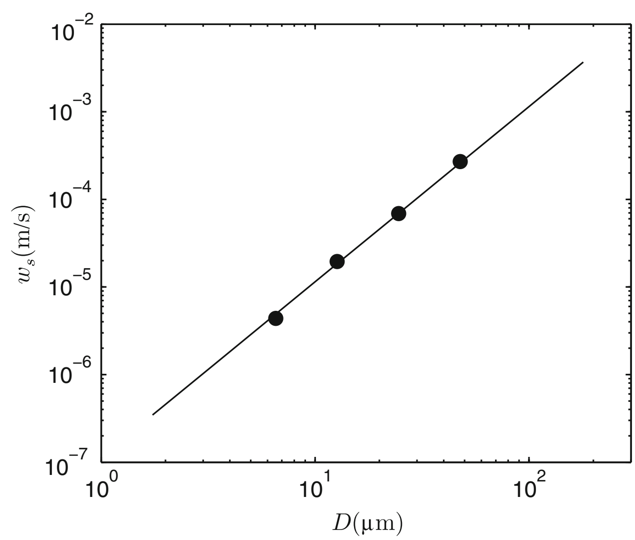

Fig. 3 Computed particle settling velocities for the size classes presenting significant concentrations and fitted Stokes' law

was fitted to the data, and the resulting particle density was estimated to be 1.2 g/cm^3, in agreement with direct estimations of the density of the hardened resin.

3 Example results

In this section, a pair of images are presented to show the advantages of using the described custom-made fluorescent particles. Figures 4 and 5 were obtained simultaneously using a Nd:YAG laser, with pulse energy of about 100 mJ, and two 4MP Powerview CCD cameras, both with 28 mm lenses and 532- and 545-nm filters, to capture the laser and the fluorescent particles emissions, respectively. The area captured by each camera was 20 cm × 20 cm, with a resolution of about 0.1 mm per pixel. This area is representative of the largest field of view that can be measured with this setup and does not represent a significant reduction compared to the setup used with nonfluorescent particles. The cameras were mounted parallel to each other, with an overlapping region of about 5 cm. The aperture was *f*/22 for the camera with the 532-nm-filter and *f*/4 for the camera with the 545-nm-filter; the difference in aperture was such that similar lighting conditions were achieved in each image. The reflective surface observed at the bottom of the images is a deposit of regular silica sand with a $D_{50} = 500$ μm, a commonly used material in sediment transport studies. The water is seeded with the custom-made fluorescent particles.

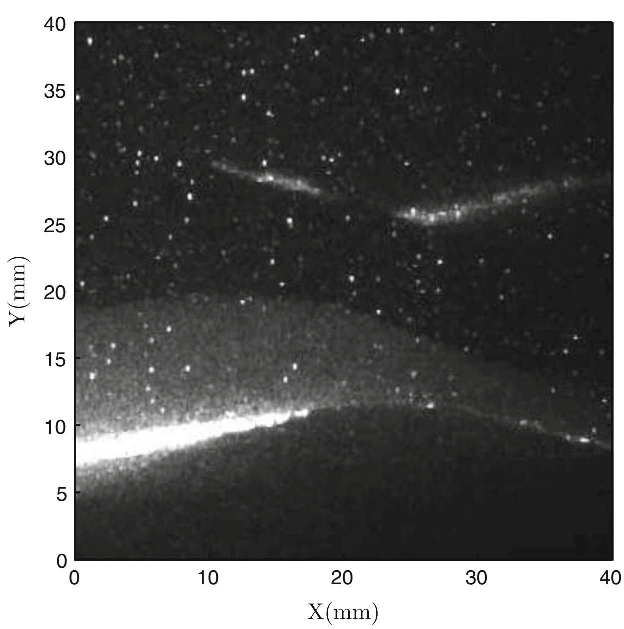

Fig. 4 Image obtained using the 532-nm-filter and fluorescent particles

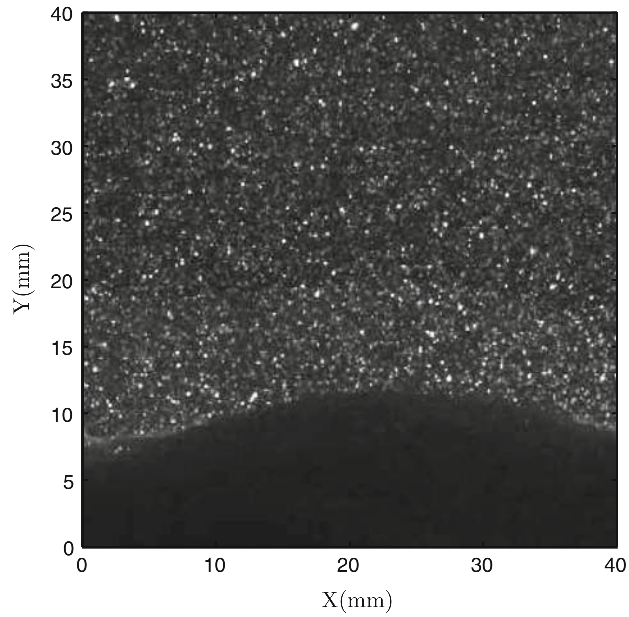

Fig. 5 Image obtained using the 545-nm-filter and fluorescent particles

In Fig. 5, a substantial improvement on the image quality over Fig. 4 is obtained by using the custom-produced fluorescent particles in combination with a filter. The complete removal of the reflected light at the bottom and other undesired reflections allows for PIV measurements very close to the sediment bed, fulfilling the main objective for using fluorescent particles. Some particles are observed on the green-filtered image, but the strong difference in particle density and the lack of cross-correlation between the images suggests that the fluorescent particles do not contribute significantly to this image, even though the resin that forms the particles has the potential to reflect some of the laser light. The imaged particles correspond mostly to impurities present in the water column, such as sand grains and bubbles. This is an encouraging result, since it implies that the produced fluorescent particles might be additionally used for two-phase flow measurements in conditions for which the dispersed phase produces a much brighter reflection than the one of the fluorescent particles.

4 Summary and conclusions

A simple and inexpensive method to produce fluorescent particles has been presented and the advantages of their use over regular particles has been discussed. A potential disadvantage of the custom-made fluorescent particles over the commercially available ones seems to be that the custom-made particles may partially reflect some of the laser light. The discussed results suggest that this effect may be negligible, allowing for the use of these particles as fluid tracers in two-phase flow measurements. Nevertheless, it is clear from the shown example that the use of the custom-made particles can certainly improve the quality of the acquired images for single-phase experiments, allowing for measurements close to laser-reflective surfaces such as a sediment beds or free surfaces.

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