

Phosphorescent tracer particles for Lagrangian flow measurement and particle tracking velocimetry

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Abstract

A new technique for manufacturing neutrally buoyant phosphorescent tracer particles for use in Lagrangian flow measurement and particle tracking velocimetry (PTV) is presented. The particles can be manufactured with inexpensive equipment and materials, using three ingredients: paraffin wax, Keywax (a wax-rubber polymer) and LumiNova® phosphorescent pigment. Particles can be made with a range of diameters (150 – 4000 µm) and when seeded throughout the flow can be excited at the peak excitation wavelength of the pigment using a focused source of ultraviolet (UV) light. Under a range of lighting conditions it is possible to excite a single particle or a chosen region of the flow to record and analyze their Lagrangian flow path. To demonstrate this technique, sample images are provided for flow in a laboratory channel with a side embayment.

Keywords: Flow visualization, PIV, PTV, phosphorescent particles, laboratory experiment

Introduction

The most common methods of flow visualization, particle image velocimetry (PIV) and particle tracking velocimetry (PTV) require small tracer particles seeded throughout the flow which approximate the motion of fluid elements. Both methods (PIV and PTV) involve the observation and measurement of the displacements and trajectories of tracer particles (that may be reflective or luminescent) from sequential or single long exposure photographs or images. While both PIV and PTV are used to develop Eulerian vector fields, only PTV is suitable for providing Lagrangian flow information (Virant and Dracos, 1997; Hardalupas *et al.*, 2000). Many hydraulic or open channel flow studies require a large field of view to capture the large scale flow features, and therefore need large bright particles for adequate visualization and image quality.

A simple and inexpensive method was developed for manufacturing spherical and neutrally buoyant particles containing a phosphorescent pigment. When illuminated by an ultraviolet (UV) light source, these particles become charged and glow brightly. With a focused light source, the particles will glow brightly for a significant length of time (i.e. tens of seconds) after the light source has been removed; or with a diffuse light source, the particles will glow brightly in contrast to the ambient light for the duration of the image capture. Using either technique, particles within a specific region of the flow can be excited, and thus tagged, and

their subsequent Lagrangian paths then observed and recorded. The motion of the particle positions can be recorded by one or more either film or video cameras for later analysis.

Particle Properties

Effective particles for use in flow visualization and tracking in large scale laboratory environments ideally exhibit the following characteristics: specific gravity similar to water; non-toxic; economical; spherical in shape; diameter less than 2 mm; rapid excitation qualities; glow brightly after excitation. Prototype particles (Bové, 2000) were made by pulverizing a mixture of lightweight epoxy resin (specific gravity, SG = 1.11) and LumiNova® pigment (SG = 3.6). However, this method created non-uniform angular shaped and negatively buoyant particles (SG of 1.42) which lost their luminescence rapidly in water. The LumiNova® phosphorescent pigment is quenched when in direct contact with water and consequently the pigment must be fully coated by the particle matrix. To eliminate quenching of the pigment and to lower the specific gravity of the particles, an alternative media, paraffin wax (SG = 0.9) was used as a coating material for creating particles (Kemp, 2002). Not only is the paraffin wax more transparent than the epoxy, allowing the particles to glow more brightly, but the hydrophobic nature and low melting point of the wax presented a simple and inexpensive method for creating small spherical particles (Fig. 1).

The wax based phosphorescent particles are made by vigorously mixing melted phosphorescent dyed wax in hot water (with a temperature greater than the wax melting point), such that small spheres form (similar to an emulsion). Once the spheres of the desired size are formed, ice water is quickly added and the particles cool rapidly and harden. A wax additive called Keywax (a wax-rubber polymer supplied by the Key Polymer Corporation – Concentrate 6-53) is added to the wax and LumiNova® mixture to increase the viscosity of the wax mixture and uniformly distribute the pigment within the wax matrix. A surfactant (i.e. Liqui-Nox® liquid detergent) is added to the hot water to reduce surface tension and assist in the formation of the spheres when creating particles smaller than 1 mm in diameter.

The wax based particles are composed of approximately 83 % paraffin wax, 14.5 % LumiNova® pigment and 2.5 % Keywax (by weight). LumiNova® is a phosphorescent pigment (LumiNova G-300, supplied by the United Mineral and Chemical Corporation, UMC), which is based on the newly developed, brightly glowing, long last $\text{SrAl}_2\text{O}_4:\text{Eu}^{2+}, \text{Dy}^{3+}$ phosphor developed by Matsuzawa et al. (1996). Particles are excited using a UV light source with wavelengths between 200 and 450 nm (UMC, 2009).

A brief summary of the particle manufacturing procedure is provided below (some specific guidelines are provided in Table 1):

1. Melt together paraffin wax (wax) and Keywax until Keywax is uniformly distributed in the wax mixture. Ratio of wax to Keywax (by mass) is 1:0.03.
2. Refer to the particle manufacturing guidelines presented in Table 1 to determine the suggested weights, volumes and mixing speed, and if required, the amount of surfactant recommended for creating the desired particle size.

3. Fill a large beaker (~ 500 mL) with approximately 250 mL of hot water and place on a hot plate at medium heat. Do not let water boil.
4. In accordance with Table 1, weigh and transfer a proportion of the wax mixture into a small beaker (~ 250 mL).
5. Add the desired amount of phosphorescent pigment to the wax mixture. For neutrally buoyant particles the ratio of pigment to wax mixture is 0.2:1, by mass. For creating heavier or lighter particles refer to Figure 2. Stir mixture and place small beaker inside the large beaker of water on the hot plate to keep dyed wax melted.
6. Fill a 4 L beaker (with fitted baffles, see Fig. 3) with ~1.5 L of hot water between 65 and 70 °C. Add surfactant if required (see Table 1) and place under a mixer with a flat rectangular mixing blade (approximately 3.5 cm wide by 5 cm long, see Fig. 3). Do not let water temperature drop below 60 °C. Fill a 2 L jug with ice water and leave beside mixer.
7. Remove dyed wax mixture from hot water bath and mix again to maintain an even distribution of pigment. Quickly pour dyed wax mixture into 4 L beaker of water and adjust mixing speed to increase or decrease particle size (based on Table 1).
8. Once particles have reached the desired diameter quickly decant the 2 L of ice water into the 4 L beaker. Once particles have hardened, remove the particles from the water using a strainer lined with a large basket-type coffee filter and lay on a flat surface to dry for at least 12 hours.
9. Dried and hardened particles can be sieved to separate sizes. Particles should be kept in a cold room or fridge until ready for use.

[For more details on the particle manufacturing process refer to Kemp, 2002].

Figure 4 shows a typical distribution of particle sizes from four different batches of manufactured particles using the instructions above. The cost of materials (wax, keywax and pigment) per unit weight is \$210/kg (or \$0.21/g). The four batches in Figure 4 represent an example of the typical yield from 339g of material (which equates to approximately \$71).

The degree to which the particles follow the fluid flow is determined by the particle and fluid properties. The Stokes number describes the magnitude of inertial effects and the fall velocity describes the effect of the relative particle density. If the particles are nearly neutrally buoyant, the fall velocity will be negligible. If the Stokes number is significantly less than one, inertial effects can be considered negligible. The Stokes number and fall velocity are a function of the particle size, relative density and temperature. Smaller particles follow the flow better; however the minimum size of the phosphorescent particle is constrained to a diameter of 150 μm to ensure adequate coating of the pigment to avoid quenching of the phosphorescence on contact with water. Size is also limited by the minimum luminescence required by the cameras for detection of the particles, which is a function of camera sensitivity.

The particle density is determined by the ratio of the metallic phosphorescent pigment to the wax and specific gravities between 0.9 and 1.3 are possible, with the upper limit constrained by the need to adequately coat the pigment (Fig. 2). Temperature affects the viscosity of water, therefore at lower temperatures the viscosity is greater and hence the fall velocity and Stokes number are lower. Temperature also affects the buoyancy of the particles due to the higher thermal

expansion coefficient of the wax compared to that of the water (Table 2) resulting in more buoyant particles as water temperature increases. It is therefore preferable to maintain a constant temperature during an experiment. Table 2 indicates the percentage density difference between the particle and the water due to a temperature increase of 1 °C for the usual range of experimental temperatures.

The particles are hydrophobic due to the oil-based nature of the paraffin wax. Adding a surfactant to reduce surface tension minimized the tendency of particles to adhere to each other, to the channel boundaries and to be trapped on the free surface. Adhesion to the channel boundaries could also be reduced by roughening the surface to minimize the contact surface (Kendell, 2001).

Image quality, which is a function of the contrast between particles and the surrounding flow, can be improved with increased particle luminescence for the conditions of no or minimal ambient light. For a given pigment loading in the particle, excitation determines luminescence. The activation wavelength of the phosphorescent pigment (LumiNova G-300) ranges between 200 and 450 nm with a peak at 350 nm and afterglow intensity increases with increased activation time and intensity (UMC, 2009). Afterglow intensity decreases exponentially with afterglow lasting up to 2000 minutes with maximum excitation. [At the time of testing between 2002 to 2004, UMC specified a peak excitation energy of 365 nm].

Experimental Application

To demonstrate the potential of these particles for use in flow visualization, two sample images are provided to illustrate two different recording techniques for capturing the flow paths of phosphorescent particles: (1) long exposure streak images (Fig. 5A); and (2) digital video of moving particles (Fig. 5B).

The flow in an open channel laboratory flume with a side embayment (0.24 m x 0.24 m) was seeded with phosphorescent particles. In the first case, the particles passing through a specific region of the flow were excited by a focused source of ultraviolet A (UVA) light for 1-3 seconds, and using the phosphorescence or afterglow, their motion was captured on a single negative (Fig. 5A). A standard 35 mm manual camera with 3200 ISO black and white film and a 52 mm lens was used to capture up to 30 second long exposure streak photographs of the glowing particle trajectories. The particles were excited using an EFOS ActicureTM UV curing lamp with a peak wavelength of 365 nm with a cable light guide, having a final aperture of 5 mm and divergence angle of 54 degrees, providing an intense spot of light.

In the second case the cable light guide was removed and the UV light positioned above the embayment to illuminate the entire recirculation and mixing regions for the duration of the image capture (Fig. 5B). The luminescence of the particles was bright enough to contrast with the ambient UV light and produce good quality images using a digital video camera (Canon OPTURA). In both cases, the images were captured in a dark room.

For the case of continuous UV illumination, improvements to image quality could be obtained with the use of an ultraviolet light filter. The peak emission wavelength of the glowing particles (520 nm) is higher than the wavelength at which they are excited by the UV lamp (200-450 nm). A cut-off filter in the range of the UV lamp emission (i.e. 455 nm) positioned in front of the camera could sufficiently improve the contrast of the glowing particles while the UV light remains on. The UV intensity could then be increased to produce a more brightly glowing particle, while not compromising the contrast of the image between glowing particles and the ambient UV light.

Conclusions

A simple and inexpensive method for manufacturing phosphorescent tracer particles for flow visualization and particle tracking has been presented. Using this simple manufacturing technique, particles can be produced with diameters ranging from 150 – 4000 μm , which are brightly glowing, neutrally buoyant, non-toxic, inexpensive and spherical in shape. When seeded in a laboratory open-channel flow experiment, the particles provided a long term observation of Lagrangian particle trajectories of individual flow paths in a highly three-dimensional and turbulent flow field. These particles can be used for flow visualization and velocimetry for a wide range of fluid dynamic and open channel flow studies.

Acknowledgements

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Figure Captions

Figure 1. Spherical phosphorescent particles with diameters ranging between 150 – 1200 μm , before (A) and after (B) excitation by UV light.

Figure. 2. Relationship between average particle density and pigment loading (ratio of pigment to combined mass of wax and Keywax).

Figure 3. Mixing reactor: 4 L beaker with fitted aluminum baffles and rectangular mixing blade (3.5 cm x 5 cm).

Figure 4. Cumulative distribution curves for four different batches of manufactured particles. Batches 1 and 2 were attempts at 1 mm diameter particles and batches 3 and 4 were attempts at 600 μm particles. Total weight of material used for all four batches was 339 g. Total yield of particles within the 600 μm and 2 mm sieves was 124.5 g (or 37 %). [Note: In these batches, particles greater than 2.5 mm are typically conglomerates of smaller particles, rather than individual large particles.]

Figure 5. Performance of phosphorescent particles. (A) Long exposure photograph taken when only a single particle passing the spot of focused UV light is excited (photo exposure duration ~ 20s). (B) Multiple particles throughout the embayment are simultaneously excited by diffuse UV light. Solid arrows indicate main flow direction. Flume boundaries (white lines) have been added in post-processing. Embayment dimensions are 24 cm x 24 cm.

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Tables

Table 1. Particle manufacturing guidelines.

| Diameter (mm) | Mass of wax mixture, WM (g) | Surfactant ¹ (mL) | Mixing Speed ² (rpm) |
|---------------|-----------------------------|------------------------------|---------------------------------|
| 1 - 4 | 20 | 0 | 200-300 |
| ~1 | 60 | 0 | 300 |
| 0.6 - 1 | 80 | 0.2 | 300 |
| < 0.6 | 100 | 0.2 – 0.8 | 300-3000* |

¹ Liqui-Nox®concentrated liquid detergent (or other suitable surfactant).

² Adjust speed according to desired particle size. Mixing speed provided is approximate and may vary with manufacturing set-up.

* The combination of a large amount of soap and very high mixing speed will create very small particles (< 150 µm) which will not glow properly.

Table 2. Percent difference (%) in density between the particle and water for a 1°C temperature change.

| Temperature (°C) | $\beta_w \times 10^3$ (°C ⁻¹) | $\beta_{pw} \times 10^3$ (°C ⁻¹) | % difference in density |
|---------------------|--|---|----------------------------|
| 10 | 0.088 | 0.495 | 0.04 |
| 15 | 0.151 | 0.691 | 0.04 |
| 20 | 0.206 | 0.985 | 0.03 |
| 25 | 0.256 | 1.961 | 0.18 |
| 30 | 0.302 | 2.360 | 0.17 |

Where β_w is the cubic thermal coefficient of expansion for water (Lide and Kehianian, 1994) and β_{pw} is the cubic thermal coefficient of expansion for paraffin wax (Clash and Rynkiewicz, 1944).

Figure 1

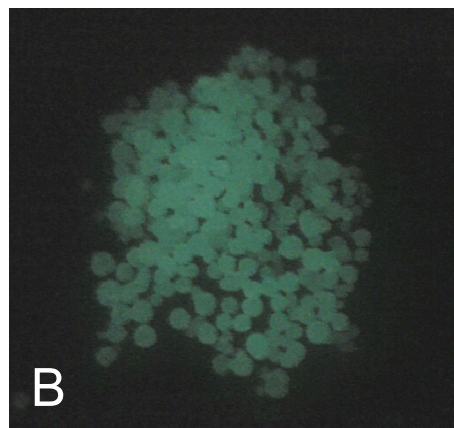


Figure 2

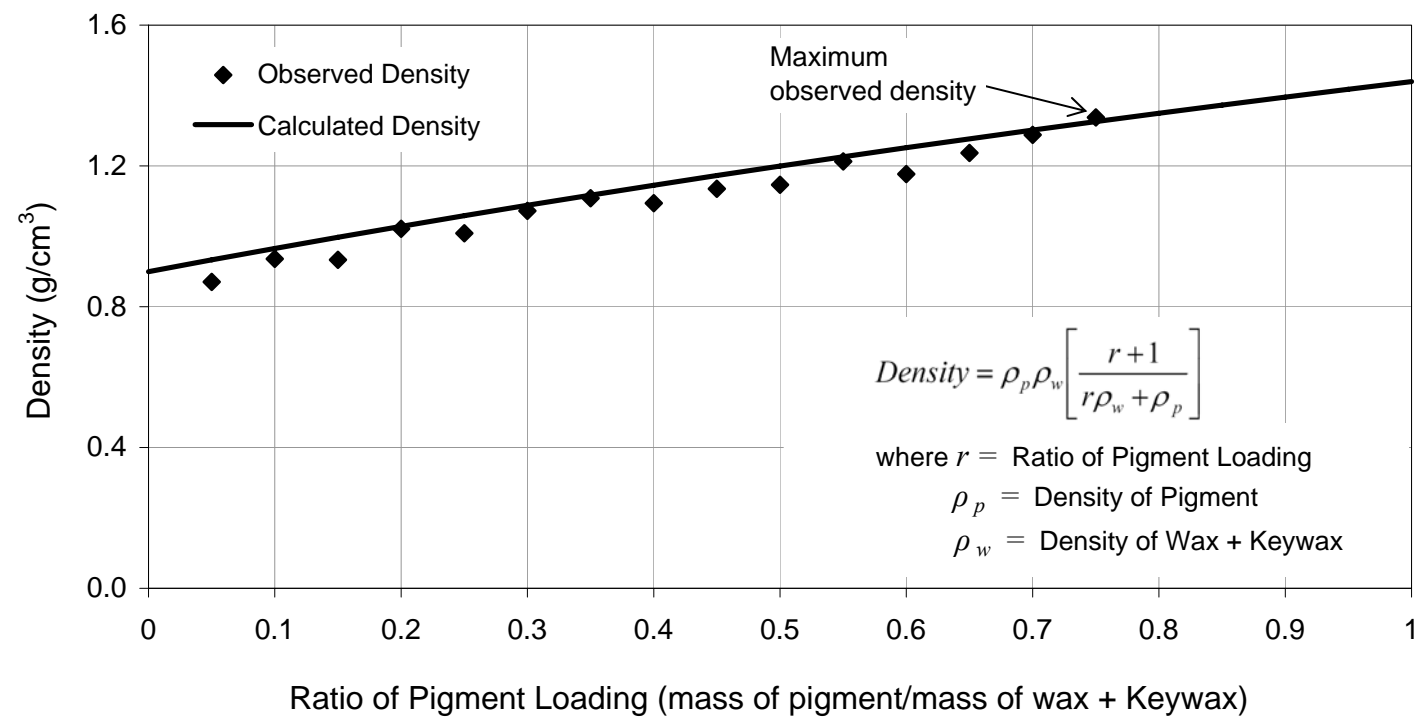


Figure 3

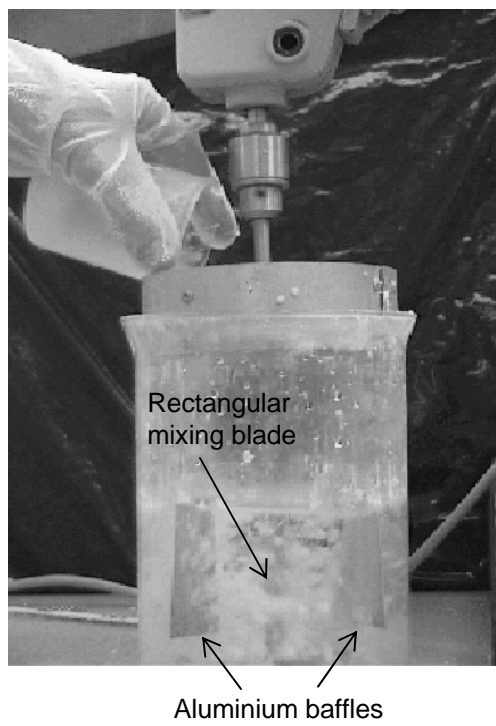


Figure 4

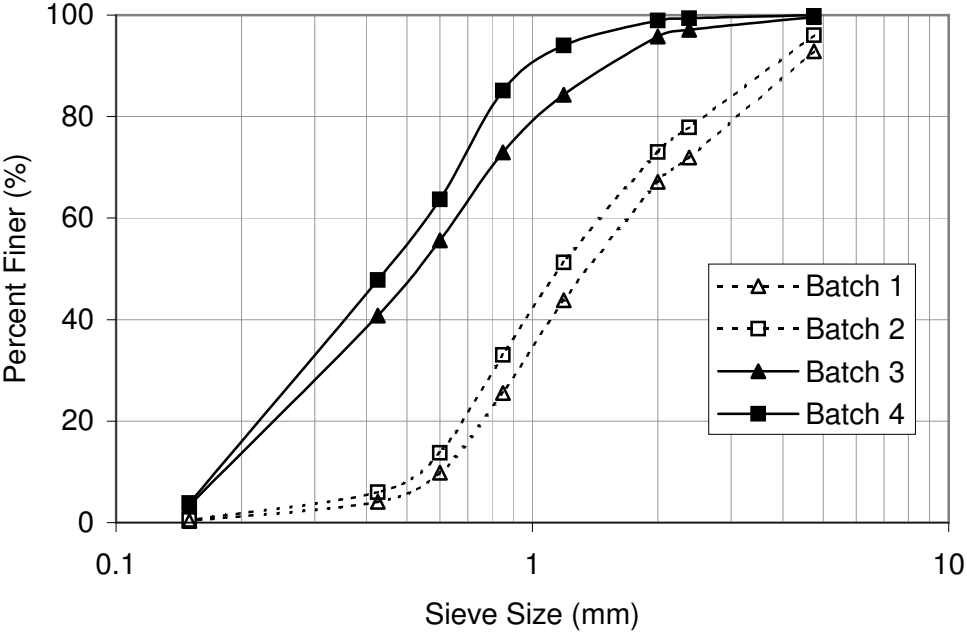


Figure 5

