Multi-camera PIV imaging in two-phase flow for improved dispersed-phase concentration and velocity calculation

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ABSTRACT

We present a multi-camera thin light sheet imaging method to accurately measure dispersed phase concentration up to optical densities of close to O[1]. The work is an extension of prior single camera methods that utilize particle image characteristics to identify particles and, when appropriately calibrated, provide a measure of the effective measurement volume thickness. By introducing multiple camera perspectives, stereo photogrammetry methods can be combined with the redundancy of information available in the images to provide 1) increased accuracy in determining individual particle locations, and 2) increased reliability in identifying all of the dispersed phase objects in the face of increasing probability of obscuration by surrounding particles. The method is calibrated through the use of a fixed solid/gel suspension test cell that mimics the optical properties of a solid/water suspension. The static arrangements of the particles allows for a repeatable volume scan of the cell, which is subsequently used to produce an accurate mapping of the particle locations within the test volume which serves as the reference set for evaluating the performance of the new method. The new method is then tested against reference cell sets of different volume fractions ranging from $C = 1 \times 10^{-4}$ to $C = 1.2 \times 10^{-2}$ for a fixed particle size of $D = 240 \mu m$. The new method is able to provide an accuracy of 2\% up to a volume fraction of $C = 8 \times 10^{-3}$, which is an order of magnitude greater than the single-camera methods used previously.

1. Introduction

Revealing the physics behind turbulent transport of two-phase flow remains an outstanding problem due to the complexity of the coupling effect between the different phases. In the current work, we aim to extend existing methods of two-phase flow measurement utilizing particle image velocimetry (PIV) to measure the concentration and velocity of turbulent dispersed suspensions of solid particles at higher volume fractions than has been previously reported using a thin light-sheet imaging method. Specifically, we will use information from multi-camera recordings to help reduce limitations created by light scattering and obscuration that occurs at higher concentrations. Although elements of this approach have been utilized for single-phase
PIV applications in a different context (3D particle tracking: Ouellette et al (2006); Tomographic PIV: Westerweel et al (2013); and Synthetic Aperture PIV: Belden et al (2010) for example), our method is unique in its approach and optimization towards higher concentrations by keeping a thin light sheet and depth of focus, and capitalizing on the constraints this places on the system. The method is validated using a static suspension test cell that mimics the optical conditions of solid/water flows (our current application of interest is for coastal sediment transport), allowing for a highly detailed characterization of the particle distribution by incremental scans of the complete cell. This information is then utilized to validate the measurement that results from using information from just a single illuminated slice of the cell, mimicking the results of a single thin-sheet observation in the actual dynamic experiment. In what follows, the approach will be outlined, followed by calibration demonstration across a 100 times variation in concentration to illustrate the benefits the method provides in comparison to single camera methods.

The most important challenge in accurately performing a two-phase PIV measurement is being able to appropriately discriminate between the motion of the dispersed phase (sediment particles for the current application) and carrier phase (tracer particles). Although many methods exist, they commonly can be categorized as separating the information optically (such as with fluorescently tagged particles: Poelma et al (2006); from details of the image characteristics: Khalitov & Longmire (2002); Kiger & Pan (2000); Knowles & Kiger (2011); or in the correlation plane: Deen et al (2002). Of these methods, use of the image characteristics is sometimes favored due to its flexibility in suitable tracer particles and illumination requirements. Khalitov and Longmire (2002) developed an algorithm to reliably separate phases based on an object’s size and brightness. Since sediment particles are much larger (about 200 times larger in cross-sectional area) than the tracer particles, a size and brightness criteria can be applied to separate the phases in many conditions of practical interest. Assuming the particle size is known, the dispersed phase volume concentration can be determined once the effective thickness of the light sheet is known, which is dependent upon the size and brightness criteria applied. Our previous work using a static test cell of solid glass spheres suspended in an aqueous gel have been conducted under various concentrations, from which the effective measurement volume is calibrated for different size and brightness criteria (Knowles & Kiger, 2011). This method works appropriately only when the dispersed phase volume concentration is small (depending on optical conditions of the dispersed phase and the experimental setup, but for our previous work, we were limited to values smaller then 0.001) such that the likelihood of multiple particles images overlapping or obscuration by particles just outside of the light sheet is small. At higher
concentrations, obscuration and overlapping particle images become more frequent, and the accuracy of this single camera approach begins to degrade. What is more, light scattering from dense sediment particles are so intense and irregular that the measurement volume cannot be accurately correlated with the size and brightness criteria any more. Without valid particle detection and accurate measurement volume calculation, it is not practically possible to come up with a satisfying dispersed phase concentration.

To extend this technique, we introduce multi-camera imaging combined with a thin light sheet as a means to provide a more precise and reliable identification of the dispersed phase in the face of increased concentration. Here both phases are illuminated by the same laser light sheet and filmed by three synchronized and calibrated cameras (the method could be generalized to more cameras). The position of the cameras for the current work is shown in Figure 1, along with images of a single particle that is offset from the center of the light sheet as seen by the three cameras. The cameras have been placed with viewing angles approximately 150° apart between cameras 1 and 3 and 1 and 2, minimizing the chance that a two neighboring particles would cause obscuration effects in all three camera images. After the phase information has been separated for all three cameras (using median filtering and size/brightness criteria as in previous methods), stereo PIV can be applied to the tracer particles in order to acquire the 3D velocity vectors of the carrier phase in the light sheet plane. The filtered image of the dispersed phase particles are subsequently used to determine their 3D positions by using standard photogrammetry methods (as exemplified by Spinewine et al, 2003). Once all the particle positions are determined, the concentration can be acquired directly by computing the volume (or number) occupied within a prescribed thickness. The benefit of this method is that once the particles are identified, the measurement volume depends much less upon the beam profile or the lighting condition, provided illumination is sufficient to allow identification of the particle in at least two cameras. The proposed technique of multi-camera imaging can also help reduce the obscuration problem due to high particle concentration. Since there is a larger chance that a particle being blocked in one camera can be detected by other cameras looking from different perspectives.

2. Calibration Method: test cell and volume scanning method

The crucial part of the above process is to accurately identify and locate the 3D positions of dispersed phase particles. To assist in the development of the technique, a static dispersed phase
A test cell is used which closely mimics the optical conditions of a solid/water mixture, as used in our previous work (Knowles & Kiger, 2011). The experimental setup is shown in Figure 1. A small box (75 x 50 x 25 mm) is filled with an ethyl alcohol gel (Purell hand sanitizer, index of refraction $n_i = 1.35$) and mixed with a known mass of sediment particles (soda lime glass spheres, specific gravity $SG = 2.5$, index of refraction $n_p \sim 1.52$, average size of $D = 240 \mu m$ sorted using

![Experimental setup diagram](image)

**Fig. 1** Experimental setup and images of a single particle as it is translated through the light sheet. Due to the oblique viewing angle of cameras 2 and 3, the particles appear to translate in the $x$-direction as the box is displaced.
along the z-axis. The difference in the apparent position from the actual position is referred to as the disparity vector (shown as white vector), and contains the information of z-position of the particle.

standard mesh sizes of 218 and 265 μm, respectively). Five different mixtures were created with nominal target volume concentrations of \( C = 1 \times 10^{-4}, 8 \times 10^{-4}, 3 \times 10^{-3}, 6 \times 10^{-3} \) and \( 1.2 \times 10^{-2} \). After calibration of the cameras, the box is placed in the field of view, illuminated with a thin laser light sheet \( (\Delta z \sim 1 \text{ mm thickness}) \), and images are simultaneously acquired on all three cameras. Following image acquisition, the box is translated \( \Delta z = 0.1 \text{ mm} \) in the direction perpendicular to the light sheet and the process is repeated. A total of 100 steps are used to generate a detailed rendering of a 10 mm thick volume within the cell. The cameras and laser light sheet are fixed throughout the translation process. Note that due to the projection of the particle image in the oblique viewing directions (cameras 2 and 3), there will be an apparent horizontal shift of the particle image due to the particle’s z-distance from the focal plane. This shift from the actual \((x,y)\) position is often referred to as a “disparity vector” and can be used to determine the z-position of the particle. Sample images of a single particle from several different z-displacements are shown in Figure 1, along with the corresponding disparity vectors.

Once the image data is acquired, the information from all of the images is used to reconstruct the “reference” data set. The reference set is used to validate the proposed technique that is expected to extract information obtained from just a single image within the volume. To start, the size and brightness method is used to identify all objects independently within the complete set (all image planes, all cameras). Then, starting with the first image plane in the set, each identified object is compared via cross-correlation to all possible objects identified within a region corresponding to the object’s expected position. For the viewing angles of cameras 2 and 3, this corresponds to an expected displacement of approximately 50 μm, or \( 0.2D \), giving a reliable means to associate the same particle throughout the entire sweep. The object in the subsequent frame with the highest correlation is selected as the most likely match. The process is then continued for the entire set, creating a “track” of the particle as the volume is swept through the light sheet. As new objects are identified, new particle tracks are created, and if existing objects have no identifiable continuation object, a track is terminated. To find the most reliable estimate of the particle locations, all of the tracks from the 3 cameras are overlaid, along with the corresponding average brightness of the particles, as shown in Figure 2. The multiple tracks should all cross at the same point for a unique particle, with a maximum of the average brightness value, corresponding to when it is in the light sheet. Two criteria are used to identify a track as a dispersed particle: 1) the peak magnitude of the average brightness and 2) the length
of the track. For the current work, a minimum track length of 1 mm (11 planes) and peak brightness of 180 units (the sensor maximum is 4095 with a background noise level of approximately 15).

Ensuring 3 independent and complete tracks through the volume, however, is only reliably possible at low concentrations, and even then is still susceptible to the influence of what choice is made for the track length and brightness requirements to identifying a particle. At the lowest concentration, 90% of the particles were identified in all three cameras (80 in total). Many of the cases not identified in all three cameras had peak brightness values and/or track lengths near the threshold. While these objects could be identified in all three cameras if the thresholds were relaxed, it was found that clearly spurious objects (dust particles in the gel, or even particle fragments) were also starting to be accepted. Clearly, performing carefully controlled tests to assist in selecting the appropriate limits should be performed for reliable particle identification. As the volume fraction increases, obscuration events and background light contamination caused by other particles begins to play a significant role in interrupting the continuation of the tracks. At the highest concentration studied, only 14% of the particles were successfully identified simultaneously in all three cameras.

To circumvent this problem, estimates are also made with information given by the intersection of only two tracks (using combination of two different cameras), and finally by selecting the brightest points along tracks distinctly visible by only one. The positions of the resulting detected particles for a single concentration ($C = 3 \times 10^{-3}$) are shown in Figure 3. Calculating the

![Fig. 2 Apparent position and brightness of a single particle as viewed by the three cameras during the translation of the test cell.](image)
concentration using the particle positions gives the measured concentrations reported in the Table in Figure 3. With the exception of the largest concentration, the measured values are within 3% of the target values, which compares within the expected uncertainty in preparing the gel mixtures based upon the mass of particles added to the original gel (conservatively ±3% to ±10%, depending on the mass of particles added, with the greatest uncertainty at the lowest concentration). The largest concentration underestimates the target value by nearly 20%. We believe that this is due to the significant obscuration effects that are present under these conditions, as will be discussed further below.

![Fig. 3](image)

**Fig. 3** The breakdown of the percentage of particles identified by the various cameras during the 3-D scan method is given in the table for all concentrations studied. The position of dispersed phase particles as determined using the full scan procedure is shown for \( C = 0.003 \).

A further check of the mixtures is made by examining the spatial homogeneity, as shown in Figure 4. Here the concentration is measured using an averaging subvolume that is \( \Delta z = 3.2 \) mm thick. This value is selected to minimize noise due to lack of statistical convergence while still
allowing for some spatial resolution. All except for the lowest concentration case show a spatial variation within ±5%. For $C = 0.0008$ and $0.003$, the variation appears random, while for $C = 0.006$ and $0.012$ a distinct bias is noted as one moves across the test cell. The bias in the larger concentrations is through to be a manifestation of the obscuration effects, particularly as the left and right cameras have a greater distance to view through the mixture as the $z$-position is increased. This will degrade the quality of the images in these two cameras preferentially over the middle camera, resulting a decreased ability to appropriately identify the particles. For the lowest concentration, the volume does not seem to be as uniformly mixed as the other conditions, with variations of up to ±50% of the total volume average.

![Fig. 4 Concentration profiles calculated across the depth (z-direction) of the test cell. The individual values are calculated using a 3.2 mm thick volume at each point to allow sufficient particles for a converged estimate.](image)

3. Multi-camera, Single-plane method

For an actual measurement, typically only a single image plane is available, rather than a whole volume created by a scan (although a high-speed scanning method could take advantage of the above previous method). To reliably identify particles and provide an estimate of their 3-D position, a multi-step particle-pairing algorithm based upon particle image cross-correlation is developed using the information from all three cameras, as outlined in Figure 5. The fundamental premise is that the image from each camera provides the apparent $x$-$y$ coordinates of individual particles, and the resulting disparity of the particle positions between any two
image pairs conveys the $z$ coordinate of the particle. Since only two perspectives are required to provide the depth information, the third camera (or more if additional cameras are used) can provide redundancy to improve the estimate or provide missing information when a particle is obscured from view of one of the cameras.

![Logic diagram of particle identification routine](image)

**Fig. 5** Logic diagram of particle identification routine for locating dispersed phase particles from only a single image.

The process is started by identifying all objects within each camera image using the size and brightness method to limit objects that are most likely close to the light sheet (limiting the maximum disparity that is possible between the 3 camera images). Once identified, a matching particle is sought in the corresponding images from the other cameras by comparing the selected source object to potential matching target objects. The comparison is facilitated by limiting the search to a region based on the estimated light sheet thickness and size/brightness criteria used. This is initially conducted with a common reference camera (comparing images between 1 and 2, and then 1 and 3). The quality of possible matches are quantified performing a cross-correlation
between the source and target image, and the one with a maximum correlation value is selected as the suitable match. The disparity vector is calculated, and for objects identified and paired on all three cameras should give consistent \((x,y,z)\) positions. If confirmed, the target particles are removed from consideration, and subsequent matches are performed. For those particles that do not have matching disparity vectors, or did not have a successful match from the other pair of cameras, the correlation is recalculated once the validated particles are removed from consideration. Finally, information from possible pairings between cameras 2 and 3 are calculated to account for particles that were not visible originally in camera 1.

**Fig. 6** Concentration measured using the multi-camera single-plane method \((C_{\text{measured}})\) as compared to the volume-scan result \((C_{\text{ref}})\). Note that given the underestimate given by the volume-scan result for the highest concentration, the nominal concentration value is used for \(C_{\text{ref}}\). Corresponding measures of the concentration provided by the standard single-camera method are indicated by the star (★).

The concentration calculated from single image is compared to that of the more accurate reference scan method for the various concentrations and a range of measurement volume thicknesses, as shown in Figure 6. Since the \(z\)-coordinates of the identified particles are known, the volume for the concentration calculation can be varied and precisely defined. The multi-camera single-plane method is shown to provide an accuracy within 2% of the volume-scan measure, provided the measurement volume thickness is limited to a range of 0.5 to 1 mm and the volume fraction is less than 0.01. Beyond these thicknesses, the method starts to systematically underestimate the true concentration, rolling off more rapidly at the very low
concentrations, and more gradually at the higher values. The roll-off point generally decreases with increased concentration, indicating a reduced thickness for the averaging volume is required, until above $C = 0.01$, all values of the thickness underestimate the concentration, consistent with the volume-scan method used to provide an alternate measure of the concentration.

The fact that there is an intermediate concentration where the region of valid measurement is actually increased over the baseline lower concentration cases is interesting and not immediately obvious, as one would expect the gradual increase in obscuration effects to produce a gradual decay in the region where accurate measurement can be completed. To investigate, the average brightness of the particles along tracks from the middle camera are shown for the different concentrations in Figure 7, along with images of representative particles within the center ($\Delta z = 0$ mm), edge ($\Delta z = 0.5$ mm) and outside ($\Delta z = 1$ mm) the light sheet. From this information, it is noted that the peak brightness of the particles initially increases with concentration, with a maximum at $C = 0.003$, and then decays, while outside the nominal light sheet, the average particle brightness increases approximately monotonically with concentration. From the typical particle images, this can be seen to result from a shift in the illumination pattern in the particles as the concentration is increased. At the lowest concentration ($C = 0.0001$), where the neighboring particles are far away (average particle spacing, $\lambda_p = (\pi/6C)^{1/3} \approx 20$ = diameters), the only effective illumination comes from the light sheet, producing a relatively small intense region on the upper surface of the particle due to reflection, and a dimmer spot due to internal refraction and inhomogeneities within the particle on the lower surface. Once the particle is outside the light sheet, it is practically no longer visible. At the intermediate concentration, ($C = 0.003$, $\lambda_p \approx 6$ diameters), light scattering from neighboring particles increases the visible cross-section of the particle while inside the light sheet, even though the scattering by particles closer to the sheet origin have reduced the overall light intensity (maximum intensity values on the particle are slightly reduced). Outside the light sheet, there is sufficient scattered light available to keep the particle visible in the image. At the highest concentration ($C = 0.012$, $\lambda_p \approx 3.5$ diameters), the particles appear as a nearly uniform intensity across their projected area with only a gradual decay in intensity as one moves from inside to outside the nominal light sheet. The early increase in the visibility of the particle due to scattered illumination from neighboring particles is what is speculated to be responsible for the initial increase in the region of valid concentration measurement depth. As obscuration effects become more pronounced at the
higher concentrations, the particles become more challenging to detect, and the region of valid measurement depth is decreased.
would likely change. As an observation, the optical depth, \( l = 4 / \pi D^2 N = 2D / 3C \) (where \( D \) is the particle diameter, \( N \) is the number density and \( C \) is the volume fraction), at our highest accurate concentration measurement (\( C = 0.006 \)) is approximately 26 mm. This is roughly twice the average viewing distance to the mid-plane of the test cell, indicating that we are well into the multi-scattering conditions with our observations. It is speculated that using a unity optical depth as a reference measure for the limit of valid measurement may be a reasonable means to extend the results of the current work to other experimental conditions (particle size and viewing depth).

5. References


