Introduction

Turbidity is the measurement of the cloudiness of a fluid and is most commonly caused by the presence of suspended colloidal solids that scatter light passing through the fluid. As an optical property of the colloidal suspension, turbidity is commonly measured using optical techniques that measure the amount of light scattered by a volume of fluid. In the field of water quality engineering, turbidity is often measured using an instrument called a nephelometer, in which a photo-detector is used to measure the amount of light scattered at a right angle to a visible-light source. The measurements made by the nephelometer are calibrated and reported as nephelometric turbidity units (NTU). When the size of suspended colloids are small (with length scales on the order of 10 microns), NTU provides a reasonable estimate of the concentration of suspended solids present in a suspension. However, when the size of suspended particles are much larger (with length scales on the order of mm or higher), the quasi-linear relationship between NTU and concentration of suspended solids is invalidated.

The AguaClara research team is interested in measuring how various parameters affect the processes of flocculation. The current method of quantifying flocculation performance involves taking time series measurements of NTU of a quiescent suspension of flocs that had been created in a controlled reactor. Ideally, one should be able to compute the efficiency of the liquid-solid separation process by observing both the rate at which NTU drops as flocs settle out by gravity and the final steady-state NTU which measures final water quality. The flocs produced by the controlled reactor, however, have length scales between hundreds of microns to mm and therefore the turbidity measurements cannot provide an accurate picture of floc sedimentation. For example, if a single 1 mm floc suspended in otherwise clear water flows into the nephelometer, its surface area will reflect a significant portion of light towards the photo-detector and the measurement will register a high NTU. Without a secondary measurement devise that can measure the sizes of particles, one cannot determine the turbidity measurement was caused by a single large floc or a suspension of small particles. While the time series turbidity measurement of mm sized flocs can be distinguished from micron sized flocs by the large variance caused by large flocs going in and out of the measurement volume, the nephelometer alone does not provide enough information to characterize flocculation efficiency. This was the motivation behind using quantitative imaging techniques to measure the sizes and settling velocities of a suspension of flocs.

Measurement Apparatus

The goal was to be able to resolve individual flocs so that measurements of size and velocity could be made for every individual particle. After some discussions with professors, a backlit particle tracking method that used a digital camera fitted with a zoom lens to track a flocs inside a Plexiglas chamber placed before a white light background was chosen.

One of the first steps of this project was to design a clear measurement chamber that had a cross sectional area depth wide enough for the largest of flocs to flow through undisturbed by the walls but thin enough to both confine motions in the plane parallel to the lense of the camera and to limit flocs from blocking one another from the camera. Motion perpendicular to the lense of the camera should be avoided because such motion will move flocs out of the focal range of the camera and cause flocs to look blurry. Moreover, the problem of flocs moving between each other and the camera should be avoided because this will lead to problems when calculating displacement. Usually, the latter problem is avoided in traditional Particle Image Velocimetry (PIV) techniques with the use of a thin laser sheet that will only illuminate a thin volume in which particle overlap is not a problem. Additionally, the chamber should be designed to allow an even distribution of flocs throughout the imaging plane; therefore, the chamber was designed to be an acute isosceles triangle with the influent entering the top of the chamber from the existing flocculation apparatus and the effluent exiting the bottom hole. Since the images would be taken after the flow of fluid into the chamber had stopped and allowed to settle into a quiescent state, there would not be any horizontal component of velocity caused by the expansion of the flow cross-section.

The imaging was done with a Basler 8-bit CCD camera fitted with a zoom lens and was supported with a miniature tripod in front of the Plexiglas chamber. The camera was connected to a PC via an IEEE 1394 (Firewire) adapter and was controlled using Vision Now, an image capture software written by Boulder Imaging. In addition to being able to adjust the focus and aperture on the lens, one can also adjust the frame rate and integration time of the camera in Vision Now to get the clearest images of the flocs as possible. Since flocs settle at low velocities, a sample rate of 2 Hz (actual sampling frequency was 2.08 Hz due to unknown limitations) was adequate the capture the range of floc settling velocities.
Image Preprocessing

All of the preprocessing and postprocessing was done using MATLAB. The pictures are in grey scale with white in the background and dark floc shadows. It was more intuitive to have a dark background, so the negatives of the images were taken to make the background black and the flocs in shades of grey. In addition to having various shapes and sizes, flocs are also very porous; therefore, each individual floc image consisted of a range of pixel sizes, colors and arrangements. It can be difficult to identify and isolate individual flocs from one another in some of the denser regions. In order to make all flocs visible and more easily identifiable, the grayscale negative images were binarized with the im2bw function and using a threshold value carefully chosen such that would turn all visible flocs white and everything else black. This threshold value was determined dynamically for each separate image by the function graythresh. Next, the function bwlabeln was called to identify each floc by determining which pixels were connected to each other. Pixels were considered connected if they are of the same color and were immediately adjacent to any of the four sides of the pixel. The function bwlabeln will create a 2D vector map of the binary image and revalue every pixel of each connected entity (floc in this case) with a number to identify them. The pixel count and centroid coordinate for each floc was computed and stored for later reference using the function regionprops. Since all flocs have their pixel count and centroid coordinate stored, one can filter out flocs for separate analysis based on their pixel size. While filtering flocs based on pixel count is an extremely useful method of generating statistics about particle size distribution and relating particle sizes to velocities, there are some errors and uncertainties related to this crude filtering technique that will be discussed in a later section.

Particle displacements

Particle displacements were determined using the cross-correlation technique similar to the one used for PIV, which applies and periodic fast fourier transform in two dimensions on a subwindow of the image. The primary difference between PTV and PIV is that in PTV subwindows must be chosen carefully such that only one particle is being tracked and reported as opposed to PIV where there are numerous particles in a subwindow but only the strongest correlation value is reported for the subwindow for all particles. This is a critical difference because there could be several flocs settling all at different speeds in any given subwindow, and if only the strongest correlation peak was reported for that subwindow, not only would information about the other less correlated peaks be lost the reported displacement would be biased and not attributable to one floc with certainty. The way the subwindows were selected was based on the centroid coordinates computed in the preprocessing stage. A long vertical rectangle was fitted around each centroid coordinate so that the centroid was located in the center of the upper half of the rectangle for the first image in the pair. Using the same subwindow coordinate for the second image in the pair, a correlation can be made for each floc and the displacement can be added to the list of statistics generated for each floc. The problem of having too many flocs in one subwindow can be alleviated by applying a filter such that only a limited range of flocs sizes are processed each time.
Unfortunately, the MATLAB code had several bugs that prevented all of the images from being processed. I am currently trying to debug the code and upgrade the algorithm. There is a need to develop a more robust algorithm for tracking the individual flocs. A significant percentage of flocs are being decorrelated during processing due to several computational shortcomings. First, flocs are identified using a connectivity algorithm that lumps pixels together as entities if any two pixels lie immediately adjacent to one another on any of the four sides. This can be a problem, however, because if two flocs happen to come into direct contact with one another in one image frame and come apart in the subsequent frame due to disparities in their settling velocities, the current algorithm will not be able to track these two particles. For instance, if a pixel count filter is applied to filter out large particles, a apparently joint floc in the first frame may pass the filter while the in the subsequent frame the same floc is shown as two separate, smaller flocs, which gets filtered out of the picture leading to decorrelation because there is no particle in the second image of the pair to perform a cross correlation. The same problem can occur for the reverse case of when two flocs are imaged in the first frame and then they settle in close proximity and thus imaged as a single large floc in the next frame. A possible solution to this problem could be to track particles over more image frames where a displacement is estimated from the first pair of images and then corroborated in subsequent frames to see if that initial estimate was correct. This is intuitively how humans are able to track objects even when they momentarily lose sight of the object during tracking—humans are able to predict where the object should be based on an estimate of its trajectory made from past observations of the objects movement. I will attempt to develop an algorithm that uses this insight.
Eventually, I would like use this PTV method as a tool to measure the flocculation efficiency as part of my ongoing research. By building up statistics on floc size and velocity, I will be able to calculate an estimate of particle size distributions and the corresponding distribution of settling velocities. These statistics can help me characterize how well certain controller parameters of flocculation affect final floc size and water quality.

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