A LABORATORY FACILITY FOR FLOCCULATION-RELATED EXPERIMENTS

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A LABORATORY FACILITY FOR FLOCCULATION-RELATED EXPERIMENTS

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ABSTRACT

This report describes the design and functions of a new experimental facility built in the School of Civil Engineering at the University of Sydney used for the investigation of flocculation-related processes. This facility was uniquely designed to replicate physical (hydrodynamic processes and sediment load), chemical (nutrients and contaminants) and biological (micro-organisms) processes in natural aqueous environment; hence, it allows for investigating the effects of these processes on the flocculation dynamics of suspended particle matter (SPM) through a fully controllable laboratory-based research. It consists of five major components, including a small-scale settling column, a turbulence generating system, a water quality measuring system, a μPIV system, and a micro-controlling system. Measurements, either imaging data of settling SPM or water quality readings, can be acquired automatically with any arbitrary scheduling. The innovation of this facility is the integration of physical, chemical and biological aquatic processes into one framework to explore the complexity of the interactions between these processes and SPM dynamics. One of its major contributions to the advancement in sediment dynamics studies is the direct detection of possible repercussions the increased anthropogenic stresses has on the microbial population and the aggregation kinematics and statistics of suspended particles in aqueous ecosystem. Ultimately, this facility is expected to contribute to a comprehensive understanding of how all possible interactions in natural water bodies affect each other and consequently, how these interactions affect SPM flocculation and transport.

KEYWORDS

Aggregation
Settling column
μPIV
Suspended particle matter Biological flocculation
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Introduction

1.1 Background

The flocculation dynamics of suspended particle matter (SPM) in surface waters have been the main area of interest in both environmental and engineering contexts for the analysis and management of water quality, the monitoring of sediment and contaminant transport (e.g., Lick and Rapaka, 1996; Tye et al., 1996) and the prediction of sedimentation rate (e.g., van Leussen, 1988; Winterwerp, 1999).

There is a wide consensus that SPM aggregation and breakup rates, its properties and characteristics (e.g., size distribution, density, porosity and internal architecture) and its settling rate and residence time are governed by numerous natural processes in aquatic ecosystem, such as, hydrodynamic processes (e.g., turbulence and differential settling Kranck, 1973; McCave, 1984), ionic interactions (e.g., Schofield and Samson, 1954; Tombacz and Szekeres, 2004), adsorption of chemicals and contaminants (e.g., Karickhoff et al., 1979; Ongley et al., 1981), presence of organic matter (e.g., fecal pellets, dead cells and metabolic products Droppo, 2001; Mietta et al., 2009) and colonisation of micro-organisms (e.g., Kiorboe, 2001; Grossart et al., 2006). Although effects of these processes on SPM flocculation have long been investigated, these investigations are often conducted independently in a labour-splitting system. For example, sedimentologists mainly focused on hydrodynamic effects on the physical attributes of SPM, which then affect SPM flocculation dynamics and sedimentation; whereas, chemical engineers and microbiologists investigated mainly the response of SPM flocculation toward a specific type of chemicals, contaminants or micro-organisms.

However, none of the above processes presents alone in natural ecosystem and, therefore, these processes may interact with one another to contribute an impact on SPM flocculation that is yet to be explored. For example, there is still lacking of a comprehensive understanding on how the change in chemical constitution of natural waters would impact the microbial communities, how hydrodynamic processes and increased sediment load can affect microbial colonization, how these interactions would affect SPM flocculation and which of these processes would have a dominating effect over the others. Hence, experiments focusing only on the effect of one controlling factor is not sufficient to answer the questions stated above. This, therefore, calls for a need to design an experimental system that can integrate the effects of all these interactions into one framework and that can allow the control of all physical, chemical and biological parameters at once.
1.2 Aim

The aim of this report is to present an experimental facility that is able to incorporate many, if not all, possible physical, chemical and biological processes governing SPM dynamics in natural aqueous ecosystem into one framework. To this end, we design a small-scale settling column equipped with a turbulence generating system that creates isotropic and homogenous turbulence field at any desirable shear rate; and a water quality measuring system that keeps track of the changes of chemical concentrations and other water quality parameters in the settling column, which can then be used to infer chemical and biological interactions. The characteristics and dynamics of SPM are analysed based on imaging data acquired using an automated $\mu$PIV system. Through the use of a micro-controlling system in this facility, experiments can be carried out automatically at any arbitrary scheduling. The criteria upon which the design of this facility bases on are listed in Chapter 2, while, detailed descriptions of the design of each component of the facility is then presented in Chapter 3.
Chapter 2

Design criteria

This experimental facility was designed to fulfil the following criteria:

1. This facility has to replicate the hydrodynamic (turbulence), sediment and nutrient characteristics found in natural water bodies.

2. This facility has to allow for the monitoring of chemical and biological processes in the control volume.

3. This facility has to be able to capture and fully preserve the detailed information of settling SPM (e.g., size, shape, morphology, fractal characteristics, settling motion, etc.).

4. This facility has to allow for instantaneous, simultaneous and automatic monitor and control of all parameters and measurements, including turbulence shear rate, sediment concentrations, chemical concentrations, SPM images and water quality readings.
Chapter 3

Facility components

To satisfy the design criteria stated in Chapter 2, this experimental facility was designed to consist of five major components: the settling column, the turbulence generating system, the water quality measuring system, the $\mu$PIV system, and the micro-controlling system (refer Chapter 5 for the photographs of the full setup). The design of each of the above components is described in details in this chapter.

3.1 Settling column

A settling column (Figure 3.1), made of Perspex, consists of three main components: a flocculation section, a diaphragm and a measuring section. The three components are fastened together with screw connections while gaskets are used in between the connections to provide water proof seal. Both the flocculation and measuring sections are filled with water and are separated by the diaphragm. The test SPM suspension is present and mixed only in the flocculation section. During measurements, a slider is moved to allow the opening of a through hole on the diaphragm and SPM is allowed to flow from the flocculation section into the measuring section. In the measuring section, SPM flow is channeled into the camera field of view, where a $\mu$PIV system is used to acquire images of settling SPM (described in Chapter 3.4).

3.1.1 Flocculation section

The flocculation section (Figure 3.1b) is the control volume where SPM suspension is tested; it has inner depth of 210 mm, inner width of 140 mm and height of 600 mm, with a total capacity of approximately 16 L. The flocculation section is partitioned into two compartments by a vertical separator; the larger compartment has a square cross-section of 140 mm $\times$ 140 mm, where the test SPM suspension is turbulently mixed; the other compartment has a size of 70 mm $\times$ 140 mm, and is used to host a water quality meter inserted vertically from the top of the flocculation section. A triangular slope was placed at the bottom of the water quality meter compartment to drive the deposited SPM into the compartment with turbulence mixing. Several holes ($1/8"$ BSP thread) equipped with elbow valves were made along the flocculation section to control overflow, to allow sampling of SPM at various depths, to drain and clean the column and to provide flexibility if insertion of other equipments is needed in future.
3.1.2 Diaphragm

The diaphragm (Figure 3.1c) separates the test SPM suspension in the flocculation section from the water volume in the measuring section, and allows only the flow of SPM into the measuring section during time at which image measurements are taken. Five sediment sampling holes of 5 mm diameter were made on the diaphragm to provide flexibility in choosing the position for SPM image acquisition. However, only one sampling hole is used at once and those not in use are temporary sealed. The opening and closing of the sampling hole are controlled using a slider connected to a two shaft 3 V DC motor through two fishing lines that run inside the flocculation section up to the top. To ensure the movement of the slider is not hindered by deposited SPM, a cleaning system, consisting of two immersible water pumps with pump outlets directed onto the slider, is used to remove deposited SPM from the slider.

Figure 3.1: Schematic drawings of (a) the settling column, (b) the flocculation section, (c) the diaphragm, and (d) the measuring section.
3.1.3 Measuring section

The measuring section (Figure 3.1d) has a size of 210 mm × 140 mm × 270 mm. A lateral access (with a choice of 3 different positions) was implemented to insert optical fibers used in conjunction with the μPIV system (described in Chapter 3.4.2). These optical fibers are fastened to a holder (as in Figure 3.8 of Chapter 3.4.2) inside the measuring section. Attached to the holder, a SPM driver is used to guide the SPM flow coming from the diaphragm by gravitational settling toward the camera field of view along a two-wall separation chamber of 5 mm width. A pipe was placed at a corner inside the measuring section to remove bubbles trapped below the surface of the diaphragm. Several additional holes were also made for draining and cleaning of the column and for future need. Note that all holes implemented are of 1/8" BSP thread.

3.2 Turbulence generating system

An isotropic (i.e., all averages relating to the properties of turbulence do not change under rotations or reflections of the coordinate system, Tennekes and Lumley, 1972) and homogenous (i.e., the mean velocity of the turbulence field is uniform in space, Tennekes and Lumley, 1972) turbulence is generated in the flocculation section by using an oscillating grid, which is a technique widely used in sediment related experiments (e.g., Wolanski et al., 1992; van Leussen, 1994; Liem et al., 1999; Gratiot et al., 2005; Maggi, 2005). The oscillating grid was designed to create a turbulence field of different intensities. The turbulence shear rate \( G \) induced by the oscillating grid was determined from the geometry, stroke and frequency of the grid using analytical and empirical equations proposed in previous literature (e.g., Hopfinger and Toly, 1976; Fernando and De Silva, 1993; Bache and Rasool, 1996; Matsunaga et al., 1999).

3.2.1 Grid geometry

The oscillating grid consists of eight horizontal square grid elements parallel to each other. Each made of diamond-shaped bars with bar diameter \( d = 6 \) mm and has 16 units of square mesh with mesh size \( M = 28.5 \) mm, resulting in a solidity (i.e., the ratio of the area of diamond-shaped bars to the total grid area) of approximately 43.75 %. The grid elements are vertically and evenly displaced by 60 mm spacing between each other, and are connected through their centers with a stainless steel rod.

The grid element was made by plastic because plastic is very light in weight, non-reactive to chemicals, non-adhesive and has high resistance to oxidation and corrosion. It was designed as square so as to be symmetrical to the flocculation section (the compartment with square cross section of 140 mm × 140 mm, described in Chapter 3.1.1). In addition, tests reported in Maggi (2005) suggested that square grid created more isotropic and homogenous turbulence field in contrast to triangular grid, thus justifying the use of square grid in ensuring the isotropism and homogeneity of the turbulence field. Furthermore, the grid was designed to a size (i.e., 120 mm × 120 mm) that gave 10 mm of clearance between the edge of the grid and the inner wall of the flocculation section. This is to provide sufficient space to introduce the slider mechanism on the diaphragm (described in Chapter 3.1.2) and yet to be small enough to minimise wall effect. The use of diamond-shaped bars enhances the turbulence field as a few studies observed that diamond-shaped prism created the strongest eddies and the highest vorticity compared to circular and square prisms (e.g., Tonui and Sumner, 2011; Ghozlani et al., 2012).
3.2.2 Oscillation control

The grid is driven through the vertical stainless steel rod by a 12 V DC motor, which is connected to a 140 mm diameter wheel and a piston of adjustable stroke $S$ (Figure 3.2b) that transformed the rotational motion of the motor into vertical motion perpendicular to the grid element plane. The adjustable stroke of the piston ranges from 10 mm to 60 mm, which corresponds to the minimum and the maximum stroke, respectively. Note that, the stroke $S$ is defined here as the distance from the top to the bottom dead center of the piston, indicating the furthest possible travel of the grid in one direction.

The downward motion of the wheel is facilitated as a result of gravitational effect and, thus, the wheel moves faster downward than upward. This irregularity of the wheel motion is reduced with the aid of tension springs attached to the piston. A driver (a hollow rigid metal tube) is used to guide the stainless steel bar connecting the grid elements to minimise any undesired rotational and horizontal oscillations.

The frequency of the grid $f_t$ (i.e., the number of oscillations per second) is measured using an electrical spring interrupter, which consists of two springs and a metal plate attached to the bottom end of the piston (Figure 3.2b). The two springs are connected to a 5 V electricity supply and a signal is detected when the metal plate touches the springs. The signal is then sent to the micro-controlling system (described in Chapter 3.5) to allow instantaneous, real-time monitoring and adjustment of the frequency.
3.2.3 Determination of turbulence shear rate

The root mean square velocity \( u \) and the energy dissipation rate \( E \) of the turbulence induced by an oscillating grid can be correlated to the geometry, stroke and frequency of the grid (e.g., Hopfinger and Toly, 1976; Fernando and De Silva, 1993; Bache and Rasool, 1996; Matsunaga et al., 1999). In this section, the approaches proposed by Hopfinger and Toly (1976) and Matsunaga et al. (1999) were tested against the grid geometry and experimental data reported in Maggi (2005). The approach that best matches the experimental data in Maggi (2005) was used to determine the turbulence shear rate \( G \) induced by the oscillating grid in this study.

**Hopfinger and Toly (1976) approach**

Based on a number of experimental observations, Thompson and Turner (1975) and Hopfinger and Toly (1976) found that at a fixed position \( z \) and a fixed stroke \( S \), the turbulent fluctuating velocity \( u \) is proportional to the grid frequency \( f_g \), i.e., \( u \propto f_g^m \) (where \( m = 1 \) for square bars and \( m = 4/3 \) for round bars). From dimensional analysis, they proposed to include a physical quantity that involves the unit of time, i.e., the kinetic viscosity \( \nu \), to account for the exponent \( m \), and that, \( u \) could be accounted for by the Reynolds number \( Re \). By varying \( S \) around a fixed \( z \), Hopfinger and Toly (1976) also observed a dependence of \( u \) on \( S \) and the mesh size \( M \). Hence, at any position \( z \), \( u \) can be written as,

\[
\frac{u}{f_g S} = F \frac{Re}{M},
\]

where \( Re = S f_g M / u \).

To derived the spatial decay of homogeneous turbulence induced by the oscillating grid, the turbulence kinetic energy dissipation rate \( E \) can be expressed in terms of \( u \) as (e.g., Batchelor, 1953; Tennekes and Lumley, 1972),

\[
E = \frac{A u^3}{l},
\]

where \( l = \beta z \) (Thompson and Turner, 1975) is the integral length scale with \( A \) and \( \beta \) being constant parameters.

From the observations that \( u \) decayed with increasing \( z \), Thompson and Turner (1975) proposed that

\[
\frac{du^3}{dz} = -B u^3
\]

where \( B \) is a constant. By integrating Eq. (3.3) with \( l = \beta z \), the corresponding \( u \) at a particular distance \( z \) from the grid can be expressed as,

\[
u = u_0 \left( \frac{z}{z_0} \right)^{-\frac{B}{\beta}},
\]

where \( u_0 \) is the root mean square velocity at \( z = z_0 \) and \( z_0 \) is the reference position. Hopfinger and Toly (1976) suggested that the reference position \( z_0 \) can be taken at \( z = M \) with \( M \) as the mesh size of the grid. Experimental results in Hopfinger and Toly (1976) showed that both \( \beta \) and \( B \) depend on the grid geometry and stroke \( S \); however, the ratio \( B/\beta \) is always constant (i.e., \( B/\beta \approx 3 \)) provided that the turbulence is homogenous. At \( z = z_0 \), \( u_0 \) can be derived based on Eq. (3.1), such that,
A LABORATORY FACILITY FOR FLOCCULATION-RELATED EXPERIMENTS

\[ u_0 = C f g S Re^{(m-1)} \frac{S}{M}^{\frac{1}{2}}, \]  

(3.5)

where \( C = 0.25 \) is a dimensionless coefficient calculated from experimental fitting in Hopfinger and Toly (1976). By substituting Eq. (3.5) into Eq. (3.4), \( u \) can be expressed as,

\[ u = C S^2 M^2 f g z^{-1} Re^{(m-1)}. \]  

(3.6)

Following Eq. (3.2), \( E \) can therefore be written as,

\[ E = A u^3 \frac{C f g S M}{\beta z^4} Re^{(3m-3)}, \]  

(3.7)

where \( A = 1 \) (Tennekes and Lumley, 1972) and \( \beta = 0.1 \) (Noh and Fernando, 1993).

The turbulence shear rate \( G \) can be derived from \( E \) as,

\[ G = \frac{C f g S M f g Re^{(3m-3)}}{\beta z^4 u}. \]  

(3.8)

Matsunaga et al. (1999) approach

In Matsunaga et al. (1999), the analytical solutions of \( E \) were derived based on the Standard \( k - E \) model, which does not require the assumption of constant eddy viscosity in the vertical direction. This gives the equation of \( E \) as,

\[ E = \frac{1}{\beta z^4} Re^{(3m-3)} \]  

(3.9)

where \( z' = k f g S^2 / \nu \) with \( k' \) and \( E' \) as the turbulence kinetic energy \( k \) and the turbulence dissipation rate \( E \) at \( z = 0 \), respectively. Both \( k' \) and \( E' \) were observed to be dependent on the grid geometry and frequency.

The dependence of \( k' \) and \( E' \) on \( f g, S \) and \( M \) was derived in Matsunaga et al. (1999) based on fittings of experimental data with the boundary conditions fixed at \( z = 0 \), such that, for \( Re < 5500 \),

\[ f g S^2 = a_1 M \frac{S}{M}^{\frac{1}{4}} Re^{2}, \]  

(3.10a)

and for \( Re \geq 5500 \),

\[ f g S^2 = b_1 M \frac{S}{M}^{\frac{1}{4}} \]  

(3.10b)

\[ f g S^2 = a_2 M \frac{S}{M}^{\frac{1}{4}}. \]  

(3.10c)

\[ f g S^2 = b_2 M \]  

(3.10d)

where \( a_1 = 8.1 \times 10^{-3}, b_1 = 8.2 \times 10^{-5}, a_2 = 6.0 \times 10^{-1} \) and \( b_2 = 4.5 \times 10^{-1} \) are curve fitting dimensionless parameters reported in Matsunaga et al. (1999). Note that, Matsunaga et al. (1999) defined \( Re \) as \( f g S^2 / u \).
Following Eq. (3.9) and Eqs. (3.10), $E$ can be derived as,

\[
E = \frac{b_1 f_g^3 S^3 M^{-1} Re}{\frac{1}{1.82 z'}} + 1 \left( -17/2 \right) \quad \text{for } Re < 5500, 
\]

\[
E = \frac{b_2 f_g^3 S^3 M^{-1}}{\frac{1}{1.82 z'}} + 1 \left( -17/2 \right) \quad \text{for } Re \geq 5500. 
\]

Finally, the turbulence shear rate $G$ can then be derived based on Eq. (3.8) and Eqs. (3.11) as,

\[
G = \left( \begin{array}{c}
E = \frac{b_1 f_g^3 S^3 M^{-1} Re}{\frac{1}{1.82 z'}} + 1 \left( -17/2 \right) u \\
E = \frac{b_2 f_g^3 S^3 M^{-1}}{\frac{1}{1.82 z'}} + 1 \left( -17/2 \right) \frac{1}{v}
\end{array} \right) \quad \text{for } Re < 5500, 
\]

\[
G = \left( \begin{array}{c}
\frac{b_1 f_g^3 S^3 M^{-1} Re}{\frac{1}{1.82 z'}} + 1 \left( -17/2 \right) u \\
\frac{b_2 f_g^3 S^3 M^{-1}}{\frac{1}{1.82 z'}} + 1 \left( -17/2 \right) \frac{1}{v}
\end{array} \right) \quad \text{for } Re \geq 5500. 
\]

**Comparison of the approaches against experimental data in Maggi (2005)**

The turbulence shear rate $G$ derived in Eq. (3.8) (*Hopfinger and Toly* (1976) approach) and Eqs. (3.12) (*Matsunaga et al.* (1999) approach) for the grid geometry described in *Maggi* (2005) (grid with diamond-shaped bars of $d = 8$ mm, square meshes of $M = 75$ mm and stroke $S = 37.5$ mm) is depicted in Figure 3.3. The values of $G$ determined using *Hopfinger and Toly* (1976) approach (Eq. (3.8)) showed a relatively good agreement to the experimental $G$ measured in *Maggi* (2005) with a slight underestimation at $f_g < 0.75$ Hz. On the other hand, the $G$ derived using *Matsunaga et al.* (1999) approach (Eq. (3.12)) showed very poor agreement and underestimated the experimental $G$ by approximately one order of magnitude. Hence, in this study, we adopted the approach proposed by *Hopfinger and Toly* (1976) to calculate the turbulence shear rate generated by the grid described in Chapter 3.2.1.

![Figure 3.3: Comparison of the turbulence shear rate $G$ calculated based on equations proposed in *Hopfinger and Toly* (1976) (Eq. (3.8)) and *Matsunaga et al.* (1999) (Eqs. (3.12)) for the grid geometry described in *Maggi* (2005) against the experimentally measured $G$ reported in *Maggi* (2005) at various grid frequency $f_g$.](image-url)
Determination of $G$ for the grid in this study

In Eq. 3.7, the experimental fitting coefficients $C = 0.25$ and $m = 1$ (Hopfinger and Toly, 1976) were derived for grids of square bars and we acknowledge that these coefficients may change when different shapes of the grid bar are used. This could also be the explanation of the underestimation observed when comparing this approach to the experimental $G$ measured in Maggi (2005) where diamond-shaped grid bars were used. Hence, after fitting the experimental data reported in Maggi (2005), we obtained $C = 3$ and $m = 0.67$ for grid of diamond-shaped bars.

The functions of $G$ (Figure 3.4) derived based on the coefficients suggested by Hopfinger and Toly (1976) ($C = 0.25$ and $m = 1$) and the adjusted coefficients ($C = 3$ and $m = 0.67$) were relatively similar. In this study, we adopted the adjusted coefficients to determine $G$.

![Figure 3.4: The turbulence shear rate $G$ determined based on Hopfinger and Toly (1976) approach (Eq. (3.8)) for the grid described in Chapter 3.2.1 as a function of the grid frequency $f_g$ with different values of fitting coefficients $C$ and $m$.](image)

### 3.2.4 Discussion

The determination of $G$ based on Hopfinger and Toly (1976) approach is strongly dependent on the assumption that the turbulence induced by an oscillating grid is fully isotropic and homogenous. The energy dissipation rate $E$ was calculated based on the assumption that the overall root mean square of the fluctuating velocity equalled the horizontal root mean square fluctuating velocity (i.e., $u = w$, where $u$ and $w$ are the horizontal and vertical root mean square fluctuating velocity, respectively). In addition, by using the proposed linear relationship of the integral length scale $l$ with position $z$ (i.e., $l = \beta z$), the turbulence velocity derived in Eq. 3.6 is proportion to $z^{-1}$ under the assumption that the eddy viscosity is constant in the vertical direction.

The turbulence induced by the oscillating grid used in this study, however, may not be ideally isotropic and homogenous. Previous studies observed that grids with solidity $> 40\%$ tended to create secondary flows, which affected the isotropicity and homogeneity of the induced turbulence (e.g., Corrsin, 1963; Hopfinger and Toly, 1976; Fernando and De Silva, 1993). Although the solidity of the grid used in this study is just slightly greater than 40%, the possibility of having secondary flows could not be eliminated. Furthermore, Fernando and De Silva (1993) observed the existence of large-scale secondary flow and much slower decay of turbulence velocity when adopting the grid with
end condition that has parallel bars adjacent to the column wall (i.e., similar to the end condition of the grid used in our study). They suggested that secondary circulation could be minimised by cutting away the grid bars at the edges so as to create reflection symmetry with respect to the column wall (Fernando and De Silva, 1993). The use of diamond-shaped bars in this study may also promote secondary circulation. The axial oscillation tests for circular, square and diamond-shaped prisms conducted in Tonui and Sumner (2011) suggested that the triangular-shaped afterbody of the diamond-shaped prism aided in the formation of large concentrations of secondary vortices. Moreover, wall effect may also affect the isotropicity and homogeneity of turbulence, even though in this study, the clearance between the grid and the column wall has been kept to the minimum. Due to the existence of secondary flow and wall effect, the assumption of constant eddy viscosity and that $u = w$ may not hold fully. However, the secondary flow and wall effect in this study are mainly concentrated at the near wall and, therefore, the assumption of isotropic and homogenous will still hold for the turbulence field in the water volume inside the grid.

### 3.3 Water quality measuring system

#### 3.3.1 Water quality meter

A multi-parameter water quality meter (TOA-DKK, WQC-24), equipped with sensors to measure up to 12 parameters, is used to measure the physical and chemical properties of the suspension tested in the flocculation section (Table 3.1).

The water quality meter has a height of 510 mm and a width of 110 mm, and is connected to a data logger with LCD digital display. The water quality meter has an internal memory capacity that can record a maximum of 3360 data and the data can be continuously and automatically measured and recorded even with the water quality meter disconnected from the data logger. For indefinite recording of data, the measured data can be communicated and saved instantaneously to a PC through a RS-232C cable connected to the data logger. The water quality meter is fully waterproof and has a submerging depth limit of 5 m (depending on the type of sensor mounted to the water quality meter).

#### 3.3.2 Parameter calibration

Prior to experiments, each of the parameters listed in Table 3.1 is calibrated according to the procedures suggested in the “Hand-held Water Quality Meter WQC-24 Instruction Manual” provided by the manufacturer of the water quality meter. Calibration curves may sometimes require for certain parameters (e.g., turbidity, $\text{Cl}^-$, $\text{NH}_4^+$ and $\text{NO}_3^-$).

**Calibration curves for ion sensors**

Ion sensors are initially calibrated based on the 2-point calibration procedures stated in the “Hand-held Water Quality Meter WQC-24 Instruction Manual”. The lowest and the highest calibration points are chosen based on the sensor measuring range stated in Table 3.1 and the concentration range of the sample to be measured. To increase the accuracy of measurement, calibration curves can be obtained by increasing the number of calibration points.

Sodium chloride powder can be used to prepare standard solutions at various concentrations for the calibration of $\text{Cl}^-$ ion sensor, while, ammonium nitrate powder can be used for $\text{NH}_4^+$ and $\text{NO}_3^-$ ion sensors. Standard solutions are to be prepared with deionized or distilled water. The ion sensors are then submerged in the standard solutions of known concentrations and the measured readings...
Table 3.1: Table of parameters measured by the water quality meter (TOA-DKK, WQC-24) equipped with the Standard and Ion modules.
standard deviation increased with increasing $C_K$.

Hence, from the results of these tests, we deduce that: (i) kaolinite suspension in tap water did not result in flocculation rate that was detectable by the turbidity sensor; (ii) the presence of other substances in the suspension could alter the turbidity values measured by the sensor; and (iii) the formation of flocs in the suspension decreased the turbidity. We then suggest that the correlation between turbidity and suspension concentration can only be established if the suspension is of the same particle size, shape and mineralogy without the presence of other substances and that the flocculation of the suspended particles is negligible.

Since the results in Figure 3.5a denote the flocculation of kaolinite suspension in tap water is negligible, the turbidity was then calibrated against known kaolinite concentrations. The correlation between turbidity $C_T$ and kaolinite concentration $C_K$ can be derived as in Figure 3.5b, such that,

$$C_K = 0.95 C_T. \quad (3.13)$$

This correlation, having correlation coefficient $R = 1.00$ and normalized root mean square error $\text{NRMSE} = 6.9 \%$, is used in experiments to estimate the concentration of kaolinite suspension tested in the flocculation section.

Figure 3.5: (a) the turbidity $C_T$ of kaolinite suspensions at different kaolinite concentrations $C_K$ over time and (b) the correlation between turbidity $C_T$ and kaolinite concentration $C_K$ suspended in tap water with no addition of other substance.

### 3.4 μPIV system

The measurement of the floc geometrical characteristics is conducted by using a micro particle image velocimetry (μPIV) system that has long been used in most areas of experimental fluid mechanics as a promising tool to detect single particle in space as well as in time, to track the flow motion and to determine the particle distribution within regions ranging from several millimeters down to a few micrometers (e.g., Grant, 1997; Santiago et al., 1998; Chakraborti et al., 2000; Maggi, 2005; Lindken et al., 2009). The μPIV system, which consists of an imaging system and an illumination system, enables the tracking of the characteristics and motion of settling SPM in an untouched environment, hence, preserving the detailed information of the SPM.
3.4.1 Imaging system

A digital charge-coupled device (CCD) camera (Prosilica GC2450) and a high magnification lens (Navitar 12X Body Tube) are used to acquire images of settling SPM. The CCD camera and the magnification lens are mounted on a height-adjustable camera stand equipped with a cooling system to prevent over heating of the camera (Figure 3.6).

The CCD camera has a size of 2448 $\times$ 2050 pixel, 8-bit grayscale depth with a frame rate of 15 Hz at full size. The magnification lens is equipped with a continuous zoom that enables variation in the field of view (FOV) over a wide range of magnification steps, ranging from 0.58 to 7.0. The size of the FOV and, hence, the size of a pixel at various magnification steps was determined through calibration against printed grids of known sizes (described in Chapter 3.4.3). The depth of field (DOF) of the lens was also qualitatively determined to be approximately $\pm$ 5 mm from the focal distance.

The CCD camera is connected to a host computer and SPM images are acquired using *Image Acquisition Toolbox* in Matlab. This toolbox allows the adjustment of camera properties (*e.g.*, gain and shutter speed) and enables automatic image acquisition at specified time.

![Figure 3.6: The CCD camera and the high magnification lens mounted on the height-adjustable camera stand.](image)

3.4.2 Illumination system

A Cree LED (cool white colour) of 3.7 W, 400 lumens is used to illuminate the settling SPM. Light from the Cree LED is transported and shined directly onto the settling SPM through optical fibers that are inserted into the measuring section. The use of optical fibers enables the light to be shined directly onto the region where the measurements are to be taken without the need for the light to travel through the Perspex wall of the measuring section, hence, minimising the attenuation of the light beam.

An optical box (Figure 3.7), made of aluminium plates, was designed to hold the Cree LED and optical fibers in place. As the Cree LED radiates a great amount of heat, aluminium plates and a fan are used to dissipate the heat and control the temperature. Four optical fibers are inserted into an aluminium tube and are placed as close as possible to the bulb of the Cree LED so as to capture the maximum light intensity.

The other ends of the optical fibers are inserted into the measuring section and are fixed onto a holder (Figure 3.8a) attached to a positioning stand (Figure 3.8b). The optical fibers are tightly fastened between two plastic plates with one of the plates having round grooves cut at different angles.
to concentrate the light beams from the optical fibers into a point where the region of measurement is. A mask of less than 1 mm opening is attached to the plastic plates to create a thin vertical light sheet. The SPM driver is attached to the optical fibers holder approximately 5 mm from the mask to channel the flow of settling SPM (as described in Chapter 3.1.3).

The optical fibers holder is held in the measuring section by attaching it onto a positioning stand. The optical fibers holder is positioned in such a way that the center of the 5 mm gap between the mask and the SPM driver coincides with the center of the hole on the diaphragm. This is to allow SPM to flow within the plane of measurement. The vertical position of the optical fibers holder can be adjusted with a slot on the positioning stand.

Figure 3.7: The optical box for holding Cree LED and optical fibers.

Figure 3.8: (a) the optical fibers holder, and (b) the positioning stand for holding the optical fibers holder.
### 3.4.3 Calibration of pixel size

The size of a pixel at various magnification steps was determined by measuring the size of the field of view (FOV) with printed grids of known sizes, ranging from 2 mm × 2 mm to 0.25 mm × 0.25 mm. The horizontal and vertical sizes of a pixel, $X_{\text{pixel}}$ and $Y_{\text{pixel}}$, respectively, can be determined as,

$$X_{\text{pixel}} = \frac{X_{\text{FOV}}}{N_x}, \quad (3.14a)$$

$$Y_{\text{pixel}} = \frac{Y_{\text{FOV}}}{N_y}, \quad (3.14b)$$

where $N_x = 2448$ and $N_y = 2050$ are the number of pixels within the horizontal $X_{\text{FOV}}$ and the vertical $Y_{\text{FOV}}$ field of view, respectively. The size of a pixel $L_{\text{pixel}}$ is then taken as the average between $X_{\text{pixel}}$ and $Y_{\text{pixel}}$.

Panels in Figure 3.9 show that the size of FOV and the size of a pixel $L_{\text{pixel}}$ decreased exponentially with increasing magnification step. At the lowest magnification step (i.e., 0.58), a pixel has a size of 4.435 $\mu$m$^2$, whereas, at the highest magnification step (i.e., 7.0), the size of a pixel is approximately 0.375 $\mu$m$^2$. In addition, the ratio of $X_{\text{pixel}}$ to $Y_{\text{pixel}}$ (Table 3.2) is relatively close to 1, signifying that the pixel is approximately a square. The horizontal $X_{\text{pixel}}$, vertical $Y_{\text{pixel}}$ and average $L_{\text{pixel}}$ pixel sizes at each magnification step are tabulated in Table 3.2.

![Figure 3.9](image)

Figure 3.9: Functions of (a) the horizontal and vertical sizes of field of view (FOV), and (b) the pixel size $L_{\text{pixel}}$ against magnification steps ranging between 0.58 and 7.0.
A LABORATORY FACILITY FOR FLOCCULATION-RELATED EXPERIMENTS

### Table 3.2: Pixel sizes at magnification steps ranging from 0.58 to 7.0.

<table>
<thead>
<tr>
<th>Magnification steps</th>
<th>( X_{\text{pixel}} (\mu m) )</th>
<th>( Y_{\text{pixel}} (\mu m) )</th>
<th>( L_{\text{pixel}} (\mu m^2) )</th>
<th>( \frac{X_{\text{pixel}}}{Y_{\text{pixel}}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.58</td>
<td>4.40</td>
<td>4.47</td>
<td>4.435</td>
<td>0.984</td>
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<tr>
<td>1.00</td>
<td>2.59</td>
<td>2.62</td>
<td>2.605</td>
<td>0.989</td>
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<tr>
<td>1.50</td>
<td>1.82</td>
<td>1.84</td>
<td>1.830</td>
<td>0.989</td>
</tr>
<tr>
<td>2.00</td>
<td>1.28</td>
<td>1.30</td>
<td>1.290</td>
<td>0.985</td>
</tr>
<tr>
<td>2.50</td>
<td>1.05</td>
<td>1.06</td>
<td>1.055</td>
<td>0.991</td>
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<tr>
<td>3.00</td>
<td>0.84</td>
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<td>0.845</td>
<td>0.988</td>
</tr>
<tr>
<td>3.50</td>
<td>0.72</td>
<td>0.73</td>
<td>0.725</td>
<td>0.986</td>
</tr>
<tr>
<td>4.00</td>
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<td>0.65</td>
<td>0.645</td>
<td>0.985</td>
</tr>
<tr>
<td>4.50</td>
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<td>0.58</td>
<td>0.575</td>
<td>0.983</td>
</tr>
<tr>
<td>5.00</td>
<td>0.51</td>
<td>0.52</td>
<td>0.515</td>
<td>0.981</td>
</tr>
<tr>
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<td>0.47</td>
<td>0.465</td>
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<tr>
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<td>0.41</td>
<td>0.405</td>
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<tr>
<td>7.00</td>
<td>0.37</td>
<td>0.38</td>
<td>0.375</td>
<td>0.974</td>
</tr>
</tbody>
</table>

#### 3.5 Micro-controlling system

A micro-controlling system consisting of an *Arduino Uno*, two motor shields and a screw shield are connected to a PC and are used to automate each component of the facility, including the regulation of the oscillating grid frequency, the control over the illumination system, the slider, the water pumps, and the image acquisition. A map of the pins on *Arduino Uno* board used to control each of these components is depicted in Table 3.3. All operations can be scheduled and carried out automatically under the supervision of a script coded in the Matlab2011b environment (Figure 3.10). All measurements, including the grid frequency and water quality parameters, are saved in a text file.

<table>
<thead>
<tr>
<th>Digital pin</th>
<th>Taken by</th>
<th>Analog Pin</th>
<th>Taken by</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>A0</td>
<td>Gridmotor (current measurement)</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
<td>A1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Electrical spring interrupter</td>
<td>A2</td>
<td>-</td>
</tr>
<tr>
<td>3*</td>
<td>Grid motor (speed control)</td>
<td>A3</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Slider motor (direction control)</td>
<td>A4</td>
<td>-</td>
</tr>
<tr>
<td>5*</td>
<td>Slider motor (speed control)</td>
<td>A5</td>
<td>-</td>
</tr>
<tr>
<td>6*</td>
<td>Waterpumps</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9*</td>
<td>Grid motor (brake control)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10*</td>
<td>CCD camera</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11*</td>
<td>Cree LED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Gridmotor (direction control)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13*</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The symbol * indicates the pin can be either used as digital or analog.

Table 3.3: *Arduino Uno* pin mapping.
Figure 3.10: The interface built in Matlab2011b environment used for monitoring and controlling all components of the facility.
Chapter

Conclusion

This report describes in details every component of a newly built laboratory facility used for investigating flocculation processes of suspended particles. The design of this facility aimed at replicating and integrating the hydrodynamic, chemical and biological processes of natural aquatic ecosystem into one laboratory-based experiment. This aim was met by adopting the use of an oscillating grid to generate isotropic and homogeneous turbulence and a water quality meter to control and monitor the chemical and biological processes in the control volume. The geometrical characteristics of suspended particles are fully preserved by using a $\mu$PIV system to acquire images of settling particles. With the use of a micro-controlling system, all parameters and measurements can be monitored and controlled simultaneously, instantaneously and automatically. This facility is expected to contribute to the discovering of the fundamental link that bridges the understanding of physical, chemical and biological interactions in waters and the flocculation dynamics of suspended particles.
Chapter

Photographs of the facility

Figure 5.1: Photograph of the experimental facility.
Figure 5.2: Components of the settling column, including the flocculation section, the measuring section and the diaphragm.

Figure 5.3: The multi-parameter water quality meter (TOA-DKK, WQC-24) equipped with Standard and Ion modules.
Figure 5.4: Photographs of (a) an grid element, (b) evenly spaced grid elements connected through a stainless steel bar, and (c) the grid oscillation system.

Figure 5.5: Photograph of the CCD camera and the high magnification lens mounted on the height-adjustable camera stand.
Figure 5.6: Photographs of (a) a Cree LED, (b) the optical box, and (c) the optical fibers holder fixed on the positioning stand.

Figure 5.7: Photographs of (a) the Arduino Uno board, (b) the motor shield, and (c) the screw shield used in the micro-controlling system.
Chapter 6

Concept drawings of the facility
Acknowledgement

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Bibliography


