ENHANCING GAS TRANSFER AT AN AIR-WATER INTERFACE THROUGH STRENGTHENED SECONDARY FLOWS MOTIVATED BY ALGAL BIOFUEL PRODUCTION

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ABSTRACT

Interest in algal biofuel production has increased significantly in recent years as alternatives to fossil fuels develop. Motivated by the desire to improve gas transfer efficiencies of open-air algae raceway ponds for large-scale algae production, we investigate a low energy, hydro-mechanical approach to enhance the direct air capture (DAC) of CO$_2$ at the air-water interface. This hydro-mechanical DAC approach has the potential to increase algal productivity rates by not only enhancing the flux of CO$_2$ into the solution, but by also enhancing the flux of O$_2$ out of the raceway pond, thus eliminating supersaturation conditions.

Secondary flows, namely, streamwise counter-rotating vortices, are known to exist in nature in wide, open channels and scale with the flow depth, $H$ (Nezu and Nakagawa, 1984). Experiments are conducted in the wide, open channel, recirculating flume (test section $L_f=15.0$ m long, $B=2.0$ m wide, $H=0.1$ m deep) in the DeFrees Hydraulics Laboratory to study the effect of counter-rotating vortices on interfacial gas transfer rates. Longitudinal half-sections of PVC pipes are used to form ridges, spaced at $2H$, to stabilize and strengthen the streamwise vortices. In situ acoustic Doppler velocimeter (ADV) and surface particle image velocimetry (PIV) measurements are used to verify their existence and characterize their strength. Surface turbulence and surface divergence measurements are obtained for three flow cases ($Re_H=\overline{U_s}H/\nu>17500$, where $\overline{U_s}$ is the bulk streamwise surface velocity) with $N=10$ ridges and are compared to three control flow cases without ridges. Oxygen transfer velocities, $k$, are determined for each flow case from dissolved oxygen
reaeration curves that are collected in accordance with ASCE (1993) guidelines. Our
findings suggest that the increased transport of fresh water parcels to the surface by
these cellular vortices (shown by elevated surface turbulence and divergence levels)
thins the concentration boundary layer, increases the concentration gradient, and
results in 9-15% higher $k$ values for the flow cases with secondary flows.
BIOGRAPHICAL SKETCH

Veronica Rose Citerone grew up in Ridley Park, Pennsylvania with her two sisters, Rose and Hollie. Their parents, Ron and Hollie Citerone, were both school teachers and always stressed the importance of education to their daughters. Veronica’s childhood summers were spent at Gandy’s Beach, NJ, at her family’s beach house on the Delaware Bay. Here, she learned to love swimming, fishing, crabbing, and exploring the marsh surrounding their house. She was always fascinated by the diverse wildlife that depended on the dynamic coastal environment.

Aside from spending time at the beach, Veronica focused much of her free time swimming competitively on various local swim teams. She continued on to swim for the Ridley High School Swim Team for four years. She developed lifelong friendships and countless memories during the many hours spent in the pool. After graduation, she spent the following summers coaching a summer swim team and managing a team of lifeguards at the pool.

Without realizing it, the countless hours she spent surrounded by water instilled in her a passion for water resources and environmental fluid mechanics. She followed this passion to the University of Delaware to study Civil Engineering. Her love of the coast led her to the Center for Applied Coastal Research (CACR) where she once again spent her summers at the beach, only this time, she was conducting cutting edge research with her engineering colleagues. Her fascinating experiences with Dr. Jack Puleo and the CACR group fostered her desire to continue on to graduate school to expand her knowledge of environmental fluid mechanics and contemporary civil and environmental engineering challenges.
This path led her to Cornell University to pursue a master’s degree, where she had the pleasure of working under the advisement of Dr. Todd Cowen and learning from others in the Environmental Fluid Mechanics and Hydrology group in the School of Civil and Environmental Engineering. She had an amazing time at Cornell and enjoyed her experiences as a graduate student in the classroom, laboratory, office, and exploring the natural beauty of Ithaca.
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Note: The author’s intentional use of “we” throughout this thesis was thoughtfully decided upon to recognize the advisement and support given to her by the aforementioned professors, graduate students, and undergraduate students, all of whom made this research possible.
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Chapter 1

Introduction

1.1 Motivation

Interest in algal biofuel production has increased significantly in recent years as alternatives to fossil fuels develop to combat the emerging concerns about greenhouse gases and global warming (Gavrilescue and Chisti, 2005). The production of biodiesel from plant and animal oils is not a new concept, as the technology has existed for over 50 years (Knothe et al., 1997; Fukuda et al., 2001; Van Gerpen, 2005). Recently, much attention has been given to the potential for microalgae biofuels to be used as realistic and sustainable alternatives to fossil fuels because of their notably high oil yield per area in comparison to other oil crops (Chisti, 2007). Table 1 describes the oil yield (L/ha) and the existing U.S. cropping area that would need to be converted to cultivation areas for different oil crops in order to satisfy 50% of the U.S. transport fuel demand. Microalgae appear to be the only renewable biodiesel source that could realistically meet the global demand for fuel (Chisti, 2007). Potential algal biofuel sources include methane produced by anaerobic digestion of algal biomass (Spolaore et al., 2006), biodiesel from microalgae oil with the residues being dried and used for animal feeds (Gavrilescue and Chisti, 2005), and photobiologically produced biohydrogen (Kapdan and Kargi, 2006).

Microalgae require CO2, a known greenhouse gas, to grow, giving them the potential to become a carbon neutral fuel source. Studies have shown that microalgae grow more efficiently when supplied with increased levels of CO2 (Maeda et al., 1995;
Brown, 1996). For this reason, several studies aim to investigate the potential for algal biofuel production facilities to use CO₂ emissions from power plants (flue gases) and chemical manufacturing plants as the carbon source for microalgae growth (Kadam, 1997; Maeda et al., 1995; Hanagata et al., 1992; Chang and Yang, 2003). This approach requires additional energy and monetary costs in order to capture, transport, and bubble or pump the CO₂ into the algae reactor. Feasibility analyses have confirmed that the potential land, water, and CO₂ resources exist to support large-scale production of algal biofuels (Sheehan et al., 1998), however, in order for algal biofuels to become a main source of commercial fuel and to compete economically and environmentally with other fuel sources, the ability to inexpensively and efficiently produce large quantities of microalgae is needed.

Table 1: Oil yield and cropping area required for different sources of biodiesel (Chisti, 2007)

<table>
<thead>
<tr>
<th>Crop</th>
<th>Oil yield (L/ha)</th>
<th>% of existing U.S. cropping area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>172</td>
<td>846</td>
</tr>
<tr>
<td>Soybean</td>
<td>446</td>
<td>326</td>
</tr>
<tr>
<td>Canola</td>
<td>1190</td>
<td>122</td>
</tr>
<tr>
<td>Oil palm</td>
<td>5950</td>
<td>24</td>
</tr>
<tr>
<td>Microalgae</td>
<td>58,700</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Currently, microalgae are produced for use as food supplements, livestock feed, stabilizing agents, soil conditioners, bioremediation organisms, and nitrogen fixing biofertilizers, in addition to many other uses (Metting and Pyne, 1986; Schwartz, 1990; Singh et al., 2005; Mallick, 2002; Kalin et al., 2005). Microalgae can be grown in tubular photobioreactors (PBRs) or open raceway ponds, and the advantages and disadvantages of both are discussed here (Figure 1.1).
PBRs are arrays of transparent tubes that allow for sunlight penetration. A mechanical pump or airlift pump is used to prevent sedimentation of microalgae within the tubes (Vunjak-Novakovic et al., 2005). High levels of O\textsubscript{2} exist in the solution because microalgae produce O\textsubscript{2} as a byproduct during photosynthesis. Supersaturation conditions of O\textsubscript{2} will inhibit microalgae productivity (Chisti, 2007). The microalgae solution is circulated through the tubes and into a degassing zone where O\textsubscript{2} is removed. CO\textsubscript{2} is injected into the tubes in various locations. Although PBRs have been shown to produce a microalgae solution with higher biomass concentration than open raceway ponds (Chisti, 2007), they can suffer from overheating, biofouling, and toxic oxygen accumulation (Hreiz et al., 2014). For large-scale production, open raceway ponds have many benefits (both environmental and energy-related) and are discussed in detail here.

Figure 1.1: a) Tubular photobioreactors b) Open-air raceway ponds

Open raceway ponds are closed-loop, recirculating channels driven and mixed by paddlewheels. Various devices for mixing have been investigated, including bubble
lifts, but paddlewheels are most commonly used because of their mechanically simple, low-maintenance design (Hreiz et al., 2014). The paddlewheels circulate the liquid in the raceway ponds at typical velocities of 0.15-0.40 m/s to ensure adequate turbulence. An experimental characterization of the hydrodynamics of raceway ponds found that the highest levels of mixing occur near the paddlewheel and bends, and that mixing is relatively poor in the straight sections (Mendoza, 2013). While proper mixing is fundamental to prevent sedimentation and ensure uniform pH, temperature, and nutrient distribution throughout the pond, extremely high mixing levels can damage the microalgae (Bitog et al., 2011). The shallow depths of the raceway ponds (10-40 cm) allow for sunlight penetration, and CO₂ is fed to the algae reactor during daylight hours.

Open raceway ponds are easier to scale up and cheaper to build, operate, and maintain than tubular photobioreactors (Chisti, 2007). In addition, they have the potential to capture CO₂ directly from the atmosphere and negate the need for additional energy required to transport CO₂ to the facility and continuously pump the gas into the liquid media during daylight hours as some algal producers do (www.earthrise.com). This research aims to investigate and ultimately improve gas transfer efficiencies at the air-water interface of raceway ponds using a hydro-mechanical approach, namely, secondary flows, to increase the direct air capture (DAC) of CO₂. Specifically, we examine streamwise counter-rotating vortices and determine their effect on gas transfer velocities in open channel flow. The hydro-mechanical DAC approach has the potential to increase algal productivity rates by not only enhancing the flux of CO₂ into the solution, but by also enhancing the flux of O₂.
out of the raceway pond to prevent supersaturation. In addition, hydro-mechanical enhancement will help ensure adequate mixing throughout the algae pond without requiring additional energy. Furthermore, the DAC approach will expand the potential geographic locations for algal biofuel production because with more efficient rates of gas transfer, the carbon source needed for optimal microalgae productivity can be completely satisfied by atmospheric CO₂ levels.

Experiments take place in a wide, recirculating flume in the DeFrees Hydraulics Laboratory. Careful measurements are obtained to compare the gas transfer efficiency of turbulent open channel flow (control cases), to flow containing strengthened, streamwise counter-rotating vortices. Oxygen is used as a proxy for CO₂ in our studies because we are interested in the direct air capture of gas from the surrounding atmosphere, and oxygen transfer can be easily and safely measured in our lab. Oxygen transfer velocities, $k$, are determined for each flow case from dissolved oxygen reaeration curves that are collected in accordance with ASCE (1993) guidelines. An acoustic Doppler velocimeter (ADV) is used to verify the existence of counter-rotating vortices in the flow and particle image velocimetry (PIV) measurements are used to describe and quantify the fluid dynamics at the air-water interface.
Chapter 2

Gas Transfer Theory and Models

2.1 Introduction

Air-water gas transfer has been studied intensively in the past few decades and continues to be a significant research topic in the scientific community because of its importance to natural environmental processes and industrial applications (Banerjee et al., 2004; Borges and Wanninkhof, 2007; Brutsaert and Jirka, 1984; Fortescue and Pearson, 1967; Liss and Slater, 1974; Rashidi et al., 1991; Wanninkhof et al., 2009). Gas exchange is a critical process in the fields of climatology, atmospheric science, public health, and environmental science and engineering.

The absorption of manmade CO$_2$ into our oceans has a huge impact on global warming and ocean acidification. Gas exchange of atmospheric CO$_2$ into the earth’s oceans prevents the gas from contributing to the anthropogenic greenhouse effect, but has been shown to lower the pH of the seawater (http://www.pmel.noaa.gov/). This process results in ocean acidification, a change to the chemistry of the seawater that has harmful biological impacts. In addition, the exchange of oxygen into water is critically important to the health of all aquatic ecosystems. Aquatic organisms depend on O$_2$ in surface water sources, and dissolved oxygen (DO) levels are often used as a measure of water quality. On a local scale, the release of volatile organic compounds from water into the air can be hazardous to the surrounding environment and community (Wanninkhof et al., 2009). Environmental engineers and public health officials are interested in predicting and mitigating the effects of harmful chemicals
and pollutants as they are transferred into our atmosphere. There are many air-water gas exchange applications in industry as well. Activated sludge processes in water treatment facilities rely on bubblers to provide oxygen to the solution in aeration tanks (Cliff and Barnett, 1988). Additionally, air stripping is an effective way to remove volatile chemicals from contaminated water and engineers must understand gas exchange rates in order to design efficient tanks (Kister, 1992).

Understanding the processes and factors that control the rate of gas transfer at the air-water interface is essential for making predictions of exchange rates in both natural environments and industrial applications. Various models attempt to relate the fluid hydrodynamics near the air-water interface to the interfacial mass transfer coefficient, $k$, where $k$ is described as a rate ($T^{-1}$) or a velocity ($LT^{-1}$), where $L$ and $T$ are the dimensions length and time, respectively. Here, we describe the most widely accepted and used gas transfer models, and discuss their relevance to our experiments.

### 2.2 Thin Film Model

The flux of any nonreactive gas across the air-water interface, in which flux is controlled by resistance in the liquid phase, can be described as

$$F = k\Delta C$$

(1)

where $k$ is the gas transfer velocity ($LT^{-1}$) and $\Delta C$ is the difference in the gas concentration between the liquid interface and the well-mixed bulk fluid (Variano and Cowen, 2008). Assuming equilibrium at the interface, Henry’s Law determines the gas concentration at the liquid interface to be equal to the saturation concentration. The classical model of gas transfer is the thin film model developed by Nernst in 1904.
(Cussler, 1984). This model assumes a steady, uniform, laminar sublayer, resulting in a linear concentration gradient between the interface and the bulk fluid. A relationship between the gas transfer velocity $k$, the thickness of the laminar sublayer $\delta$, also referred to as the concentration boundary layer, and the molecular diffusivity of the fluid $D$, can be expressed as

$$k = \frac{D}{\delta}$$  \hspace{1cm} (2)

from Fick’s first law of diffusion. The challenge, here, is determining an accurate estimation of the laminar sublayer thickness, which is assumed to be constant in all space and time, yet depends on the physical properties of the dynamic turbulent flow of the bulk fluid. Many field and laboratory gas transfer experiments have shown major discrepancies between the predicted $k$ values from this model and those measured (Wanninkhof et al., 2009). More recently, the concentration boundary layer has been treated as a temporally and spatially dynamic sublayer dependent on the characteristics of the flow near the interface.

2.3 **Surface Renewal Model**

The first Surface Renewal (SR) model was proposed by Danckwertz (1951) and was an improvement to the Surface Penetration model presented by Higbie (1935). This model is based on the theory of renewal events at the interface, where packets of fresh water are transported to the surface by turbulent eddies in the flow. The model proposes that the gas transfer velocity $k$ is related to the molecular diffusivity of the fluid $D$ and the mean time between surface renewal events $\tau$ as
Here, the determination of \( \tau \) has been defined in various ways by different researchers in attempts to correlate their observations of so-called “surface renewal eddies” with their gas transfer measurements (Tamburrino and Gulliver, 2002). O’Connor and Dobbins (1958) first attempted to relate \( \tau \) to easily measured bulk parameters of a given flow and estimated \( \tau \) as

\[
\tau = \frac{H}{U}
\]  

(4)

where \( H \) is the depth of the flow and \( \bar{U} \) is the mean streamwise velocity. Fortescue and Pearson (1967) later developed the Large-eddy SR model and assumed the mean time between surface renewal events to be

\[
\tau = \frac{L}{\sqrt{u'^2}}
\]  

(5)

where \( L \) is the bulk turbulence integral length scale and \( \sqrt{u'^2} \) is the rms velocity fluctuation of the bulk flow, a measure of the strength of the turbulent transport, where \( u' \) is determined from the Reynold’s decomposition of \( u(t) \) given as

\[
u(t) = \bar{U}(t) + u(t)'
\]  

(6)

Here, \( u(t) \) represents the time series of streamwise velocity data and \( \bar{U}(t) \) is the time averaged velocity. In this model, \( \tau \) is meant to represent the mean turnover time of the largest eddies.
Banerjee et al. (1968) and Lamont and Scott (1970) proposed the small-eddy SR model where $\tau$ is related to the kinematic viscosity of the fluid $\nu$ and the turbulent energy dissipation rate $\varepsilon$ as

$$\tau = \frac{\nu}{\varepsilon}$$

which is known as the Kolmogorov time scale. In this model, $k$ is driven by the mean turnover time of the small-scale eddies, which is described by the Kolmogorov scales.

Attempts were made to experimentally identify specific surface renewal events in order to estimate the mean time between them, but the identification of upwelling events was rather ambiguous and led to large discrepancies between the measured gas transfer rates and the model predictions (Komori et al., 1989).

### 2.4 Surface Divergence Model

The surface divergence (SD) model, proposed by McCready et al. (1986), suggests that the gas transfer rate is controlled by near-surface interface-normal motions which can be computed using the velocity field as described by the integrated continuity equation,

$$w_i = -\left(\frac{\partial u_i}{\partial x} + \frac{\partial v_i}{\partial y}\right)z = -\beta z$$

where $w_i$, $u_i$, and $v_i$ are the surface velocities in $z$, $x$, and $y$, respectively, and $z$ is oriented normal to the interface (Turney and Banerjee, 2013). Here, $\beta$ represents the terms in parenthesis, which describe the divergence of the surface velocities, or the vertical velocity gradient. The strength or magnitude of the surface divergence is
thought to be a driving force of gas transfer as it indirectly represents the rate of fresh water parcels brought to the surface, i.e. a measure of surface renewal. The surface divergence model relates $k$ to the bulk rms of the divergence, $\overline{\beta'} = \sqrt{\langle (\beta')^2 \rangle}$ where $\beta'$ values are the fluctuations from $\beta$ in time computed at each location in our PIV field of view to obtain the ensemble averaged rms value, as

$$k = c\sqrt{D\overline{\beta'}}$$  \hspace{1cm} (9)

where $c$ is an empirical coefficient that depends on the flow. This model has been used extensively to describe interfacial transfer, and typical values of $c$ from various experiments are described in Table 2.

Table 2: Surface Divergence Model Coefficients (Turney and Banerjee, 2013).

<table>
<thead>
<tr>
<th>Author/s</th>
<th>Experiment Description</th>
<th>Coefficient, $c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCready et al. (1986)</td>
<td>Counter-current wind shear</td>
<td>0.71</td>
</tr>
<tr>
<td>Law and Khoo (2002)</td>
<td>Grid-stirred tank and wind waves</td>
<td>0.22</td>
</tr>
<tr>
<td>McKenna and McGillis (2004)</td>
<td>Grid-stirred tank</td>
<td>0.50</td>
</tr>
<tr>
<td>Banerjee and Macintyre (2004)</td>
<td>Low wind flow</td>
<td>0.35</td>
</tr>
<tr>
<td>Turney et al. (2005)</td>
<td>Low and moderate wind flow</td>
<td>0.50</td>
</tr>
<tr>
<td>Magnaudet and Calmet (2006)</td>
<td>Channel flow</td>
<td>0.60</td>
</tr>
<tr>
<td>Xu and Khoo (2006)</td>
<td>Grid-stirred tank and wind waves</td>
<td>0.20</td>
</tr>
<tr>
<td>Herlina and Jirka (2008)</td>
<td>Grid-stirred tank</td>
<td>0.33</td>
</tr>
</tbody>
</table>
This model is advantageous because recent technological advances in experimental fluid dynamics, specifically the development of particle image velocimetry (PIV) techniques, have given us the capability of collecting direct measurements of the surface velocity field.

Recently, Turney and Banerjee (2013) developed a simplified model to estimate $k$ in open channel flows in the absence of wind. Their model relates easy-to-measure flow parameters to $k$ as

$$k = 0.037 \sqrt{\frac{D \overline{U}_s}{H}} \left[ \left( \frac{\overline{U}_s H}{\nu} \right)^{\frac{3}{4}} - \left( \frac{\overline{U}_s H}{\nu} \right)^{\frac{2}{3}} \right]^{\frac{1}{4}}$$

(10)

where $D$ is the molecular diffusivity, $\overline{U}_s$ is the mean surface velocity, $H$ is the water depth, and $\nu$ is the kinematic viscosity of the fluid. Limited experimental data is available to support these models and further investigation and validation are needed.
Chapter 3

Secondary Flows

The term secondary flow refers to any flow structure that is superimposed on the primary bulk flow, usually with a strength that is an order of magnitude smaller than the primary flow. Over the past century, various secondary flows have been observed in lakes, rivers, and oceans. Historically, mariners and river engineers documented the existence of longitudinal, parallel streaks of foam, bubbles, or debris on the ocean surface (McWilliams et al., 1997). This phenomenon was later explained by the existence of organized, longitudinal, counter-rotating secondary flows called Langmuir cells (e.g., Nepf, Cowen, Kimmel, and Monismith, 1995). Similar structures have been detected in straight, wide, open-channel flows, although they result from a different physical process. These three-dimensional flow patterns have been studied extensively in the field of hydraulic engineering because of their influence on sediment suspension and the development of sand ribbons in rivers.

The origin of these cellular, counter-rotating vortices is attributed to both turbulence anisotropy and transverse gradients of the Reynold’s stresses in open-channel flows (Nezu and Nakagawa, 1984). In nature, these generation mechanisms are forced by irregularities in the channel geometry and non-uniform boundaries at the bed and free surface. Regions of upflow and downflow occur at the locations of surface flow convergence and divergence, respectively, and the cellular structures scale with the flow depth, $H$. Kinoshita (1967), through the analysis of aerial photography of rivers, discovered that the typical spacing of the upwelling zones was
twice the flow depth. Culbertson (1967) and Karcz (1973) studied the spacing between the ridges and troughs of the sand ribbons in river flows, and also reported the spacing between two longitudinal ridges to be $2H$, as seen in Figure 3.1.

![Figure 3.1: Schematic of a pair of streamwise counter-rotating vortices. The diameter of the cells scales with the depth of the flow, resulting in a spacing of $2H$ between sand ridges that develop due to sediment transport at regions of upflow.](image)

Longitudinal roughness strips or ridge elements have been used in laboratory experiments to simulate the effect of sand ribbons in stabilizing and maintaining pairs of counter-rotating vortices with diameters equal to $H$ (Nezu and Nakagawa, 1984, Sanjou et al., 2014). Laser Doppler anemometers and hot-wire anemometers were used to obtain vertical, horizontal, and transverse velocity measurements at various spatial locations in the secondary flows. The aforementioned studies provided detailed descriptions of the turbulent structures of secondary currents, specifically the existence of relatively slow moving, very turbulent upflow ($w>0$) over the ridges, and faster, less turbulence downflow ($w<0$) over the troughs, where $w$ is the vertical velocity component. Field velocity measurements of cellular secondary currents are difficult to
obtain, however, because their magnitude is typically only 5\% of the mainstream velocity.

The specific effect that secondary cellular currents have on interfacial gas transfer rates has yet to be explored. Gulliver and Halverson (1989) conducted air-water gas transfer experiments in open channel flows and documented the existence of large streamwise vortices. They hypothesized that the upflow from the secondary currents was the primary source of surface renewal driving gas transfer. Their experiments, however, did not force secondary flows using ridges or roughness strips, and therefore are inconclusive in comparing gas transfer rates of open-channel flows that contain stabilized secondary cellular currents to flows without. Our experiments aim to directly compare the rates of gas transfer for both cases (with and without ridges) in order to better understand the influence of secondary flows on interfacial gas transfer rates.
Chapter 4

Experimental Methodology

4.1 Wide Open Channel Recirculating Flume

Experiments take place in a wide, open channel, recirculating flume in the DeFrees Hydraulics Laboratory (Figure 4.1). The flow is driven by two digitally controlled axial pumps that are housed beneath the outlet. Water is pumped through two 16-inch diameter return pipes and into the inlet section of the flume. Before entering the test section, the turbulent water passes through a stainless steel grid (10 x 10 cm square openings) and a mesh of honeycomb material (0.64 cm circular openings), both intended to break down any flow structures developed in the pipes. The experimental test section is $L_f = 15.0$ m in length, $B = 2.0$ m wide, and 0.64 m deep. A flow depth of $H = 0.1$ m is used for all experiments because it represents the depth of a typical microalgae raceway pond. This depth provides an aspect ratio of $B/H = 20$.

![Figure 4.1: Schematic of the wide, open channel, recirculating flume and experimental test section (not drawn to scale). For a more detailed model, see Figure 5.6 in Section 5.1.5.](image-url)
The origin of the coordinate system used in this research is located with \( x = 0 \) at the start of the test section and positive toward the end of the test section, \( z = 0 \) on the bed with positive direction upwards, and \( y = 0 \) at the side wall closest to the wind tunnel with positive direction toward the opposite wall determined with the right hand rule (on Figure 4.1 positive \( y \) goes into the page). In Chapter 6, Section 6.1, ADV measurements are presented to verify the existence of pairs of counter rotating vortices. The origin of the ADV coordinate system \((x_{ADV} = 0, y_{ADV} = 0)\) is located at \( x = 9.4\) m and \( y = 0.7\) m, where \( x = x_{ADV} + 9.4 \) and \( y = y_{ADV} + 0.7 \) (Figure 4.2). Surface PIV results are presented in Section 6.2 and the origin of the coordinate system \((x_{PIV} = 0, y_{PIV} = 0)\) is located at \( x=9.4\) m and \( y=0.7\) m as well, such that \( x = x_{PIV} + 9.4 \) and \( y = y_{PIV} + 0.7 \) (Figure 4.3).

![Figure 4.2: Location of ADV cross-section measurements. See Section 5.2 for further detail.](image)
ADV measurements, taken close to the surface \((z/H = 0.7)\) for the middle flow case \((f_p = 2.8 \text{ Hz})\), at 2 m increments from the inlet to the outlet for flow cases with and without ridges, confirm that the free surface flow is strongly affected by turbulence at all locations in the test section (rms values > 5\% mean streamwise velocity), and can be seen in Figure 4.4. Although high levels of turbulence are observed in the inlet, a trip rod is placed at \(x=0\) m, i.e. the beginning of the test section, to accelerate the growth of the boundary layer and ensure fully developed flow.
Figure 4.4: ADV measurements taken at 2 m increments down the length of the flume at z/H = 0.7 to ensure that the free surface is strongly affected by turbulence. a.) RMS values for the middle flow speed ($f_p = 2.8$ Hz) without ridges. b.) RMS values for the middle flow speed ($f_p = 2.8$ Hz) with N=10 ridges. The solid lines represent the RMS values in the trough at $y = 1$ m, and the dashed lines represent the RMS values above the 5th ridge at $y = 0.9$ m.

4.2 Experimental Cases

The flow depth, $H$, is held constant at 0.1 m for all of our experiments. We consider three streamwise flow velocities in our experiments, each representative of the typical velocities used in algae raceway ponds. We increase the pump frequencies, $f_p$, to achieve higher flow velocities, described by the temporal and spatial mean surface velocities, $\overline{U_s}$, from our PIV results. Gas transfer experiments are conducted at these three flow velocities for cases with N=10 ridges, and for cases without ridge elements (control cases). Details of each experimental case are outlined in Table 3.
Table 3: Experimental cases.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>H (cm)</th>
<th>N\textsubscript{ridges}</th>
<th>f\textsubscript{p} (Hz)</th>
<th>( \overline{U_s} ) (cm/sec)</th>
<th>Re\textsubscript{H}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0</td>
<td>1.6</td>
<td>17.6</td>
<td>18700</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0</td>
<td>2.8</td>
<td>31.6</td>
<td>33600</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0</td>
<td>4.9</td>
<td>56.3</td>
<td>58300</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10</td>
<td>1.6</td>
<td>16.4</td>
<td>17500</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>10</td>
<td>2.8</td>
<td>29.7</td>
<td>31600</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>10</td>
<td>4.9</td>
<td>53.9</td>
<td>55900</td>
</tr>
</tbody>
</table>

In order to simulate sand ridges on the bed of the wide flume in the DeFrees Hydraulics Laboratory, we use longitudinal, parallel rows of two-inch diameter PVC pipes, cut in half, and spaced at twice the flow depth (Figure 4.5). At a flow depth of 0.1 m, 10 longitudinal PVC ridges are required to span the width of the flume. Bars are numbered 1 through 10 from \( y = 0 \) m to \( y = 2 \) m, or left to right when facing the inlet from the outlet. Table 4 describes the spanwise position of each ridge.
Figure 4.5: Experimental setup of PVC ridges in the wide flume.
Table 4: Spanwise position of each longitudinal PVC ridge in the wide flume. Ridges are placed at positions $y/H=1$ and $y/H=19$ to force symmetry at the boundaries.

<table>
<thead>
<tr>
<th>PVC Ridge #</th>
<th>Spanwise Position, $y/H$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
</tr>
<tr>
<td>7</td>
<td>13</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>19</td>
</tr>
</tbody>
</table>
Chapter 5

Measurement Techniques

5.1 Gas Transfer Velocity Measurements

5.1.1 YSI Dissolved Oxygen Probe

The DeFrees Hydraulics Laboratory is equipped with YSI Dissolved Oxygen (DO) Probes (see <http://ceeserver.cee.cornell.edu/mw24/>, Laboratory Documentation – Sensors – Dissolved Oxygen – YSI) and a data acquisition system (DAQ) used to convert the analog signal to a digital voltage reading. A permeable membrane is placed over the silver cathode at the end of the probe (Figure 5.1)

![Figure 5.1: YSI DO probe with permeable membrane.](image)

The DO probe utilizes the fact that an applied potential voltage can reduce O$_2$ to H$_2$O and the rate at which oxygen diffuses through the membrane is proportional to the oxygen concentration in the solution. The reduction of O$_2$ to H$_2$O at the silver cathode produces a current that is measured in the meter. The DO probe is plugged into a...
black box labeled “Signal Conditioning Box”. An Ethernet cable connects the channel labeled “Dissolved Oxygen” to channel 17 on the DAQ black box (SCX 1 Module 1 Analog Input). A DAQ system (DAQ card: National Instruments SCXI 1300) converts the signal and records the digital voltage at a sampling frequency of 1 Hz using EasyData on a DELL Dimension 4100 computer (ID 128.84.245.215).

A careful calibration is needed to convert the measured voltage to a dissolved oxygen concentration (mg/l). Typically, a linear two-point calibration procedure is used; one point being the measured voltage at zero oxygen concentration, and the other being the voltage reported at a known saturation concentration for a particular water temperature. This method assumes that water temperature is constant during the duration of the experiment. Our experiments often run for over 24 hours and we encounter significant temperature increases due to the heat produced by the pumps as well as fluctuations in the air temperature of the laboratory. If not accounted for, this change in temperature will lead to significant errors during the calibration from voltage to concentration. A thorough examination of the DO probe’s sensitivity to temperature was performed and a detailed description of the calibration procedure is described here.

5.1.2 Dissolved Oxygen Saturation Concentration

The dissolved oxygen saturation concentration in water depends on temperature, barometric pressure, and salinity. Benson and Krause (1984) developed a set of empirical equations that compute the solubility of oxygen in water as a function of temperature, with correction factors for pressure and salinity. Their equations have
been adopted by the U.S. Geological Survey to determine oxygen saturation concentrations in water for various applications, and will be used in this research as well.

\[ C_{DO_{sat}} = \exp \left[ -a + \frac{b}{T} - \frac{c}{T^2} + \frac{d}{T^3} - \frac{e}{T^4} \right] \]  

(11)

\[
\begin{align*}
a &= 139.34411 \\
b &= 1.575701 \times 10^5 \\
c &= 6.642308 \times 10^7 \\
d &= 1.243800 \times 10^{10} \\
e &= 8.621949 \times 10^{11}
\end{align*}
\]

Here, \( C_{DO_{sat}} \) is the dissolved oxygen concentration at saturation in mg/l, and \( T \) is the water temperature in Kelvin. Over the course of our gas transfer experiments, the slight variations in barometric pressure and the very low salinity concentrations in the water have negligible effects on saturation concentration (see Appendix C for calculations). Therefore, the Benson and Krause correction factors for pressure and salinity are unnecessary. A graphical representation of Equation 11 is shown in Figure 5.2.
Figure 5.2: Dissolved oxygen concentration at equilibrium with varying temperature, constant barometric pressure, and zero salinity, calculated using the Benson and Krause (1984) empirical formula.

5.1.3 Temperature Compensation

The permeability of the membrane used with the DO probe is highly dependent on temperature and must be accounted for in the calibration process. YSI reports that the permeability of the membrane increases about 5% per degree C, but the relationship between permeability and measured voltage is rather ambiguous. We directly determine the relationship between temperature and voltage output by recording the voltage output response of the probe in fully saturated water as the temperature increases from 8 to 32 degrees C. Ice is used to drop the temperature of the test water. Submergible pumps are used to add high levels of turbulence in the bucket to ensure the water remained fully saturated during the test. The pumps also aid in warming the
A HOBO thermistor is used to measure temperature at 1 Hz during the test. The relationship between temperature and the recorded voltage at saturation is linear as seen in Figure 5.3, and an empirical function between the saturation voltage $V_{\text{sat}}$ and temperature $T \, (^\circ C)$ is determined.

![Figure 5.3: DO probe saturation voltage as a function of temperature.](image)

$$V_{\text{sat}} = 0.0059T + 0.0743 \quad (12)$$

This function is used in our calibration equation to calculate the saturation voltage as the water temperature fluctuates during our gas transfer experiments. This method corrects for the temperature driven variability in the membrane permeability.

A similar test is used to determine the temperature dependence of the voltage output at a dissolved oxygen concentration of zero mg/l. Sodium sulfite and cobalt chloride are added to a bucket of water to remove all of the dissolved oxygen (see
Appendix B for chemical concentrations). Ice is added and submergible pumps are used only to heat the water. The bucket is tightly sealed to prevent all gas transfer. The results show a negligible dependence on temperature as seen in Figure 5.4, and confirm that we do not need to correct the zero concentration voltage, \( V_o \), for changes in temperature.

![Figure 5.4: DO probe voltage reading as a function of temperature at a dissolved oxygen concentration of zero mg/l.](image)

5.1.4 Voltage to Concentration Calibration Equation

A calibration equation used for accurately converting voltage values to DO concentrations has been developed.

\[
C_{DO}(t) = \left( \frac{C_{DOsat}(T(t)) - C_{DOo}}{V_{sat}(T(t)) - V_o} \right) (V(t) - V_o)
\]

(13)
Here, $C_{do}$ (mg/l) is the true dissolved oxygen concentration in the bulk fluid as a function of time. $T(t)$ is the water temperature as a function of time collected by the thermistor during the entirety of the gas transfer experiment. $C_{do}$ is the dissolved oxygen concentration in the water at the start of the experiment after all of the oxygen has been removed and is effectively zero for all of our experiments (see Section 5.1.5). $V_{sat}$ is the temperature corrected saturation voltage and varies in time with changes in water temperature. $V_o$ is the voltage output at the beginning of the experiment when the dissolved oxygen concentration is zero mg/l. $V(t)$ is the recorded voltage as a function of time during the experiment.

Water temperature must be recorded at one-minute intervals during each experiment. The thermistor sampling frequency was chosen based on the typical time scale of measureable changes in temperature over the course of our gas transfer experiments. For our experiments, we see temperature fluctuations of less than 0.005 degrees C per minute, so it is not necessary to sample any faster than once per minute.

5.1.5 Determination of Gas Transfer Velocity

Various methods exist for measuring oxygen transfer in clean water. The standard method, and the one we are using, involves the removal of dissolved oxygen from a water sample followed by measurements of dissolved oxygen concentration as reaeration takes place (ASCE, 1993). In situ measurements of dissolved oxygen concentration can be made using membrane probes, or pumped samples can be analyzed using the Winkler or probe method. A reaeration curve is produced and a gas
transfer rate or velocity can be calculated by solving the first order differential flux equation using a mass balance approach (Equation 14) and determining the $k$ value that best fits the measured data. A least-squares approach is used to fit the model to our experimental data.

$$ F = \frac{V}{A} \frac{dC_{DO}}{dt} = k\Delta C $$  \hspace{1cm} (14)

As explained by Henry’s Law in Section 2.2, $\Delta C = C_{DO_{sat}} - C_{DO}$. With this substitution, Equation 14 can be expanded, rearranged, and solved as follows:

$$ \frac{dC_{DO}}{dt} + \frac{A}{V} k C_{DO} - \frac{A}{V} k C_{DO_{sat}} = 0 $$  \hspace{1cm} (14.1)

$$ C_{DO} = c_1 \exp\left(-\frac{A}{V} k t\right) + C_{DO_{sat}} $$  \hspace{1cm} (14.2)

Initial Condition: at $t = 0$ s, $C_{DO} = 0$ mg/l

$$ C_{DO} = C_{DO_{sat}} \left(1 - \exp\left(-\frac{A}{V} k t\right)\right) $$  \hspace{1cm} (15)

In Equation 15, $k$ is a gas transfer velocity, $A$ is the interfacial area, and $V$ is the volume of water in our flume. In order to isolate the test section as the interfacial area of gas transfer during the experiments, the inlet and outlet areas were covered by thin plastic sheets to prevent the exchange of oxygen in these regions, as seen in Figure 5.5.
The interfacial area of the test section is calculated as

\[ A = l \times w = 15m \times 2m = 30m^2 \]  \hspace{1cm} (16)

The volume of water in our flume was most precisely determined by collecting dimension measurements with a tape measure and utilizing AutoCAD to develop a 3D model of the flume. Care was taken to accurately measure all sides and sections of the flume. The return pipes have a 16-inch inner diameter. The 3D model can be seen in Figure 5.6 with dimensions in meters. The depth of the water in the test section is denoted as \( H \), where \( H=0 \) is the glass bed of the flume. The total volume of water in the flume for our tests with \( H=0.10 \) m is 15.73 m\(^3\), i.e. 15,730 liters.
5.2 **ADV Measurements**

5.2.1 Convergence of Uncertainty to Determine Record Length

Single-point ADV measurements are used to characterize the mean and turbulent velocities in the flow, verify the existence of counter-rotating vortices, and validate the results of our surface PIV measurements. A Nortek Vectrino ADV is placed at a distance of 9.4 meters from the inlet ($x=0$) at the channel centerline and a vertical position $z/H = 0.5$. For the convergence test, we orient the ADV such that its axial coordinate ($\hat{z}$) is in line with the streamwise flow. With the ADV, we record a time series of $u$ (streamwise), $v$ (transverse), and $w$ (vertical) velocity components, where $\bar{U}, \bar{V},$ and $\bar{W}$ are the temporal mean velocities, respectively, at a single point. To
determine the record length required to resolve the secondary flow velocity components, a one-hour measurement is recorded and the bootstrap method is used to verify the convergence of the data.

The bootstrap method resamples the time series of ADV velocity data and generates 1000 replicate records from which a mean velocity can be calculated (Efron and Tibshirani, 1993). For each velocity component, the 95% confidence interval of the mean value is determined at every time increment in the time series. The means of the replicates are sorted from lowest to highest to determine the upper and lower bounds of the 95% confidence interval, which are the 25th and 975th ordered values, respectively. The difference between is the high and the low values describes the 95% uncertainty in our measured mean value and is shown to decrease with increasing record length as seen in Figure 5.7. A record length is chosen based on a tolerable uncertainty level and a realistic record length. For our three flow velocities, a 10-minute record length ensures that we are 95% confident that the calculated mean values of $u, v,$ and $w$ are all within $\pm 0.04$ cm/sec ($\pm CI/2$) of the true mean velocities.
Figure 5.7: Results from the bootstrap method showing statistical convergence of the data as a function of ADV record length. ΔCI is the difference between the high and low ordered mean values. We are 95% confident that the true mean values of u, v, or w are within ± ΔCI/2, at a given record length.

5.2.2 Vectrino ADV Orientation and Configuration

At a sampling frequency of 50 Hz, we collect 10-minute single-point ADV measurements at multiple transverse and vertical locations between the 4th and 5th PVC ridges in the flow, where the center of the 4th ridge is y/H = 0 and the center of the 5th ridge is y/H = 2. The red points in Figure 5.8 denote measurements made with the ADV oriented with its axial coordinate (\( \hat{z} \)) in line with the streamwise flow (u), and is referred to as the lateral orientation, while the blue points represent
measurements made with the axial coordinate ($\hat{z}$) in line with the vertical component of velocity in the flow ($w$), also referred to as the vertical orientation.

![ADV measurement locations and probe orientations between two PVC ridges.](image)

Figure 5.8: ADV measurement locations and probe orientations between two PVC ridges.

The axial coordinate on the ADV provides the most accurate velocity measurements due to Vectrino geometry and should be aligned with the velocity component of interest. In our case, we are interested in resolving the vertical and transverse velocity components at many locations in a very small area in characterize the properties of the secondary flow structures. The lateral probe orientation, as opposed to the traditional vertical orientation, is advantageous for our purposes because it allows for a greater range of vertical motion of the probe, allowing for measurements to be made nearer the free surface in the shallow flow. We take
measurements at 3.7 cm below the surface. With this orientation, the fluid measurement volume is located 5 cm upstream of the ADV receiver and is not disrupted by the presence of the probe in the flow. Additionally, this orientation prevents some of the acoustic Doppler noise often associated with vertically oriented ADVs in glass-bottomed flumes.

The vertical probe orientation is advantageous for different reasons. This orientation allows for measurements to be taken at vertical positions below $z/H = 0.3$, very close to the bed as well as near the longitudinal PVC ridges where we observe strong vertical velocities. Further, this position utilizes the precision of the axial coordinate to measure the vertical velocity component in the flow. Figures 5.9 and 5.10 show the lateral and vertical probe orientations, respectively. Details on the ADV configuration can be found in Table 5.

Figure 5.9: Lateral ADV probe orientation and corresponding coordinate system.
Figure 5.10: Vertical ADV probe orientation and corresponding coordinate system. Probe is drawn at an offset from the actual test location for viewing purposes. The ADV was aligned with the test location during data collection.

Table 5: Nortek Vectrino ADV Configuration

<table>
<thead>
<tr>
<th>Configuration Parameter</th>
<th>Observed/Chosen Value for all Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>S/N Ratio (dB)</td>
<td>&gt; 15.0</td>
</tr>
<tr>
<td>Correlation (%)</td>
<td>&gt; 85.0</td>
</tr>
<tr>
<td>Sampling Frequency (Hz)</td>
<td>50.0</td>
</tr>
<tr>
<td>Record Length (min)</td>
<td>10.0</td>
</tr>
<tr>
<td>Nominal Velocity Range (cm/sec)</td>
<td>± 30.0 to ± 100.0</td>
</tr>
<tr>
<td>Sampling Volume (mm)</td>
<td>7.0</td>
</tr>
<tr>
<td>Transmit Length (mm)</td>
<td>1.8</td>
</tr>
</tbody>
</table>
5.3 **PIV Measurements**

5.3.1 **Introduction**

Particle image velocimetry (PIV) is a powerful and robust experimental technique used extensively in various fluid dynamics applications to collect series of instantaneous velocity measurements in a 2D plane. Small, neutrally buoyant particles, called seeding, are added to a flow. A CCD camera is used to collect pairs of high-resolution images of the seeded flow field as it is instantaneously illuminated by a light source (often a laser). A cross-correlation algorithm is used to analyze the image pairs to determine a mean discrete pixel displacement at each chosen sub-window in the image field of view. Pixel displacements are converted to physical velocities using the known elapse time between two consecutive images in a pair, Δt, and a spatial calibration to convert from pixels to physical units.

For each of our experimental cases, surface PIV is used to collect the surface velocity data needed to quantify the properties of the flow in order to better understand the processed contributing to gas transfer at the interface. Pliolite VTAC-L particles are used as seeding in our experiments. These particles, manufactured by OMNOVA, have a mean specific gravity of 1.03 and particles with diameters in the range 420-600 microns are used to allow the individual particles in our images to be on the order of two pixels. Sieves are used to sift the particles to obtain only particles in this range. The worst case particle Stokes number \( \text{Stk} = \frac{\tau_R}{\tau_\eta} \) is 0.003 calculated using the diameter of the largest particle \( d_p = 600 \) microns, the specific gravity (S=1.03), the kinematic viscosity of the water (\( \nu \)), and the turbulent dissipation (\( \epsilon \)), where
\[ \tau_R = \frac{(S-1)d_p^2}{18\nu} \]  

(17)

\[ \tau_\eta = \sqrt{\frac{\nu}{\varepsilon}} \]  

(18)

Because \( Stk \) is much less than 1, the particles will follow the behavior of the fluid very closely.

An Imperx IGV-B2020 12-bit CCD camera, also referred to as the BOBCAT, is used for imaging in our experiments. The BOBCAT is outfitted with a 50 mm lens with an aperture setting of \( f/1.4 \), and attached to the laboratory ceiling at the center of the test section, parallel to the flume bed (Figure 5.11). This particular lens is chosen after careful consideration because it allows us to focus on a very thin surface layer while capturing a wide enough field of view (FOV) to resolve four PVC ridges (from center to center), i.e. four pairs of counter-rotating vortices. In addition, a significant amount of red food dye is added to the water to attenuate the light that illuminates the FOV so that only particles on the surface are illuminated, and any particles below the surface are not captured in the image.
The BOBCAT camera has a 2060 x 2056 pixel array. We orient the camera such that our FOV contains 2060 pixels in the spanwise direction (y), and 2056 pixels in the streamwise direction (x) of our flow. The spatial resolution of our images, determined by a spatial calibration image shown in Figure 5.12 is 0.0385 cm/pixel. Therefore, our FOV covers a spanwise distance of 79.31 cm, and a streamwise distance of 79.07 cm. The streamwise flow in our images is moving from the top to bottom. For more information on the PIV FOV and coordinate system please refer to Section 4.1.
Figure 5.12: Spatial calibration image (zoomed in with Matlab). Ruler is placed at the height of the water surface (z=10 cm above the bed).

5.3.2 Timing of Strobe Lights and Image Capture

The surface of the flow in our experiments is not perfectly smooth, so a laser sheet is not an appropriate light source to illuminate the 2D surface plane. Two Elinchrom 500 watt/s strobe lights (Model: Elinchrom 500 Professional Studio Flash System Elinca Sa CH-1020 RENENS) are used to provide adequate illumination to our FOV. The strobes are mounted on tripods and stationed on the wind tunnel approximately 4.5 m upstream of the test section (Figure 5.13). The strobe heads are estimated to be located approximately 5.5 m from the PIV FOV at an elevation of 2.5 m above the water surface. Shoot-through umbrellas are used to diffuse and distribute the light. The
flash power of the strobe lights, controlled by the sliding flash variator, is reduced to 1/4th the maximum power to prevent image saturation.

Figure 5.13: Strobies mounted on tripods on wind tunnel.

For each of our three chosen flow cases, particles on the surface will move at different speeds, so the appropriate elapse time between two consecutive images is adjusted accordingly. An established rule-of-thumb is that particles should move approximately 8-12 pixels between two consecutive images. ADV measurements of the bulk streamwise flow and the spatial resolution are used to estimate an appropriate Δt for each flow case, allowing for an estimated displacement (Δx) of ~10 pixels. As seen in Table 6, the required Δt for our three flow cases is less than 67 ms (1/frame rate), the BOBCAT’s limit for acquiring two successive images in single exposure
mode. For this reason, double exposure mode is used, and $\Delta t$ is controlled by the time between two strobe flashes.

Table 6: Estimated $\Delta t$ between two consecutive images for three flow cases.

<table>
<thead>
<tr>
<th>Pump Frequency (Hz)</th>
<th>Bulk Flow Velocity (cm/sec)</th>
<th>$\Delta t$ (ms)</th>
<th>$\Delta x$ (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>16.3 - 17.6</td>
<td>25</td>
<td>~10</td>
</tr>
<tr>
<td>2.8</td>
<td>29.7 - 31.6</td>
<td>15</td>
<td>~10</td>
</tr>
<tr>
<td>4.9</td>
<td>53.9 - 56.3</td>
<td>10</td>
<td>~10</td>
</tr>
</tbody>
</table>

The strobe lights are wired to an analog out channel on a National Instruments DAQ card SCB-68 that is connected to a computer. Upon receiving a digital signal from Matlab, the DAQ card generates a 5 V signal, and a 2n2222 transistor is used as a switch to short the trigger in the strobe flash sync socket to activate the flash. A picture of the breadboard with transistors is shown in Figure 5.14 and a sketch of the breadboard circuit is shown in Figure 5.15.
Figure 5.14: Breadboard with transistors. Red and black wires are connected to the white DAQ box and blue cables connect to the strobe lights.

Figure 5.15: Sketch of breadboard with transistors used for strobe triggering.
In double exposure mode, two images are captured using a single trigger pulse. After receiving a trigger pulse, the camera immediately begins integrating the first image. The exposure of this image is controlled by the pulse width programmed into the DAQ Matlab code. After exposing the first image, the camera transfers the information to the vertical and horizontal registers and immediately begins capturing the second image (less than 200 ns delay). The exposure time of the second image is set by the time required to read out the first image. The exact integration time of the second image capture is not relevant to us, because we are working in the dark and we use the strobe lights to set the exposure time. This is easily controlled with our Matlab code. A typical timing sequence is shown in Figure 5.16. For our PIV image collection experiments, the image pair sampling frequency is set to 1 Hz and the number of image pairs collected is 900 (15 minutes of data).
Figure 5.16: Timing plot created with Matlab DAQ trigger code. In this example, the camera starts integration at 20 ms at the rising edge of the BOBCAT trigger signal (black line), and will integrate for the entirety of the pulse width: 5 ms. Strobe 1 is triggered by the rising edge of the red line ($t = 21$ ms) and strobe 2 is triggered by the rising edge of the blue line ($t = 46$ ms) during the period where the camera is reading out the first image and capturing the second. Here, $\Delta t = 25$ ms, and is controlled by the time between the rising edges of the two strobe trigger signals. The pulse widths of the strobe signals are arbitrary since the strobos flash immediately on the rising edge of their signal.
5.3.3 Imperx BOBCAT Configuration

Bobcat GEV Player is the software used to control the settings on the BOBCAT camera. The following configuration is used for our PIV imaging.

**Bobcat Configurator**

> **Trigger:**
  - Trigger in: External
  - Mode: Double
  - Over Trigger: Off
  - Edge: Rising Edge
  - Debounce: One Hundred Micro Seconds
  - Acquisition Control: [1, 1, 0]

> **Exposure:** Pulse Width

> **Data Out:**
  - Taps: Two
  - Speed: Normal
  - Depth: Mono12
  - Shift: No Shift

**Imaging Saving Settings**

> **Tools – Image Saving Options**
  - Format: TIFF Non-normalized
  - File name: Image ID, decimal number
  - Throttling options: Save one image out of every 1 captured.

5.3.4 PIV Algorithm

The PIV images are analyzed using a version of the original FORTRAN algorithm discussed in Cowen and Monismith (1997) that has been converted from FORTRAN to Matlab language (Liao and Cowen, 2005). After images are pre-processed using either a background subtraction or a minimum pixel intensity method (discussed further in Section 6.2.6), they are partitioned into 32 x 16 pixel subwindows. A cross-correlation technique is used to determine the location of the first subwindow of the
A local median filter and an adaptive Gaussian filter are used to remove erroneous displacement values. Our images are analyzed in two sequential passes of the entire data set: the first pass determines an estimate for the initial mean pixel displacement at each subwindow and this information is then used in the second pass to dynamically locate the subwindow in the second image. The resolution of our PIV data is 32 x 16 pixels per subwindow with a 50% subwindow overlap to increase the number of vectors reported.
Chapter 6

Results and Discussion

6.1 ADV Measurements of Counter-rotating Vortices

6.1.1 Mean Velocity Measurements

Our ADV measurements confirm the existence of counter-rotating vortices in the flow. Details on the coordinate system used for these measurements can be found in Section 4.1. As previously discussed, we define $z/H=0$ as the bed of the flume, with positive $z$ pointing upward to the free surface, $y_{ADV}/H=0$ as the middle of the 4th ridge from $y=0$ (location $y=0.7$ m), and $y_{ADV}/H=2$ as the middle of the 5th ridge (location $y=0.9$ m). An adaptive Gaussian window (AGW) filter was used on all of our ADV time series to remove noise peaks and preserve the normally distributed temporal velocity data (see Section 6.1.3 for a more information on the AGW filter). We compute the temporal mean of our $u$, $v$, and $w$ velocity data at each point in our grid.

The velocity vectors composed of $\overline{V}$ and $\overline{W}$ components are shown in Figure 6.1. We observe relatively strong, positive $\overline{W}$ velocities above the ridges and weaker, negative $\overline{W}$ velocities in the trough. We see slightly positive, near zero $\overline{V}$ velocities from $1<y/H<2$ and negative $\overline{V}$ velocities from $0<y/H<1$, which confirm the existence of two cells rotating in opposite directions. Interestingly, most of our ADV measurements show a slight negative $\overline{V}$ component and the counter-rotating vortices are only able to overcome this current to result in slightly positive $\overline{V}$ velocities in the downflow in the trough. This slightly negative transverse current is attributed to a
difference in performance between the two axial pumps, i.e. one pump is a bit stronger than the other. This minor difference is enough to drive a bit of a negative current in the flume but does not prevent the formation and stabilization of counter-rotating secondary cells between the ridges.

Figure 6.1: $\vec{V}/\bar{U}_x$ and $\vec{W}/\bar{U}_z$ velocity vectors for three flow cases with increasing pump frequency.

Figure 6.2 shows a series of pseudo colored plots created with Matlab’s ‘pcolor’ function. The mean streamwise velocity at each grid point for the three flow cases is shown. The diverging $\vec{V}$ velocities near the bed in the trough and the positive $\vec{W}$ velocities that occur over the ridges transport slower, more turbulent fluid to the area above the ridges. Faster, less turbulent fluid is carried down from the surface in
between the ridges. Additionally, $\bar{U}$ is higher in the trough and lower above the ridges because the ridges protrude up into the flow, adding a no-slip boundary and additional drag. The properties of the $\bar{U}$ cross-sections are typical of open channel flow.

![Graph](image)

Figure 6.2: $\bar{U}$ (cm/sec) velocities at each grid point in the cross section.

Cross-sections of $\bar{V}$ for each flow case are shown in Figure 6.3. $\bar{V}$ is generally positive from $1<y/H<2$ and negative from $0<y/H<1$ in the lower half of the cells ($z/H<0.5$). In the region closer to the free surface ($z/H>0.5$), $\bar{V}$ seems to move toward being negative from $1<y/H<2$ and positive from $0<y/H<1$ because the vortex is going in the opposite direction as it completes a full circle.
Figure 6.3: $\overline{V}$ (cm/sec) velocities at each grid point in the cross section.

Cross-sections of $\overline{W}$ for each flow case are shown in Figure 6.4. The notable features in these plots are the positive $\overline{W}$ velocities above the ridges and the negative $\overline{W}$ velocities in the trough. It is also clear from these plots that the strength of the upflow and downflow depends on the strength of the streamwise velocity. $\overline{W}$ velocities, both positive and negative, increase with increasing pump frequency.
Figure 6.4: $W$ (cm/sec) velocities at each grid point in the cross section.

Figure 6.5 shows transverse profiles of the mean velocities normalized by $U_s$, $(\bar{U}/U_s\ ,\ \bar{V}/U_s\ ,\ \text{and}\ \bar{W}/U_s\ )$ at $z/H = 0.5$. We see that the strength of $\bar{V}$ and $\bar{W}$ depends directly on the strength or magnitude of $U_s$. The strongest transverse velocities observed at this vertical location in the flow are approximately 2% of $U_s$, and the strongest vertical velocities are 3%. $\bar{U}$ is greatest in the center of the trough. $\bar{V}$ is almost always slightly negative because of the pump induced current, but we see stronger negative values from $0<y/H<1$, and almost positive values from $1<y/H<2$. $\bar{W}$ is negative in the center of the trough and positive over the ridges.
Figure 6.5: Transverse profiles of $\overline{U}/\overline{U}_s$, $\overline{V}/\overline{U}_s$, and $\overline{W}/\overline{U}_s$ at $z/H = 0.5$.

### 6.1.2 RMS Turbulence Measurements

In order to better understand the general properties of the secondary flows in our experiments, turbulence intensities are computed at each location in the ADV grid. Root mean squared (rms) turbulence fluctuations, are calculated as

\[ u_{rms} = \sqrt{u'^2} \]  \hspace{1cm} (19)

\[ v_{rms} = \sqrt{v'^2} \]  \hspace{1cm} (20)

\[ w_{rms} = \sqrt{w'^2} \]  \hspace{1cm} (21)
where $u'$, $v'$, and $w'$ represent the differences between the measured velocities and the temporal mean velocities at each instant in time, i.e. the turbulent fluctuations as previously defined in Chapter 2.

Turbulence is generated by shear in the flow. The largest velocity gradients occur near the bed and ridges where the velocity increases from zero at the bed to some nonzero free stream velocity. The streamwise, transverse, and vertical turbulence intensities are higher at locations close to the bed and ridges, and are slightly less intense in the center of the trough. In general, the highest turbulence intensities are observed near the bed and above the ridges (Figures 6.6, 6.7, and 6.8). The upflow over the ridges carries slower, more highly turbulent fluid toward the free surface. The downflow between the ridges carries faster, less turbulent fluid toward the bed. The typical turbulence intensities measured in our flow are approximately 2-15% of the maximum streamwise flow for each flow case.
Figure 6.6: Streamwise turbulence intensities, $u_{rms}/\overline{U}$, at each ADV measurement location in the flow.

Figure 6.7: Transverse turbulence intensities, $v_{rms}/\overline{U}$, at each ADV measurement location in the flow.
Figure 6.8: Vertical turbulence intensities, $w_{rms}/\bar{U}_s$ at each ADV measurement location in the flow.

Spanwise profiles of $u_{rms}/\bar{U}_s$, $v_{rms}/\bar{U}_s$, and $w_{rms}/\bar{U}_s$ at $z/H = 0.5$ are shown in Figure 6.9. Turbulence intensities are shown to be highest at $y/H = 0$ and $y/H = 2$ (above ridges), and lowest at $y/H = 1$ (in trough), as described above.
Figure 6.9: Spanwise profiles of turbulence intensities $u_{rms}/U_s$, $v_{rms}/U_s$, and $w_{rms}/U_s$ at $z/H = 0.5$.

6.1.3 Post-processing Techniques

An AGW filter is used to post-process the ADV data and was originally developed by Cowen and Monismith (1997) and distributed for use by our research group. The statistics of our ADV time series are calculated and used to iteratively remove unwanted noise peaks in our data while retaining the random turbulence fluctuations. Minimum and maximum velocity thresholds can be given as inputs to the filter, but we set these to extreme values (>1000) because the AGW filter works very well on our data without these constraints. In the first iteration, the median (more robust than mean) and an estimate of the standard deviation (based on the inter-quartile range) of
the data sample are calculated. The code is written such that when a value in one velocity component is flagged and removed, the corresponding values of the two other velocity components are removed from the time series as well. Less than 5% of any time series of our ADV data is removed by the AGW filter.

6.2 Surface PIV Measurements

6.2.1 Mean Surface Velocity Fields and Spanwise Profiles

Our post-processed PIV results for the three flow cases both with and without ridges are presented here. We use the time series of PIV velocity measurements to compute a streamwise ($\bar{U}$, cm/sec) and transverse ($\bar{V}$, cm/sec) mean surface velocity field for each experimental case (Figures 6.10 and 6.11). In addition, we compute spanwise mean surface velocity profiles by averaging the data spatially in $x$ for all $y/H$ locations (Figures 6.12, 6.13, 6.14, and 6.15).

The signature of a large pair of counter-rotating vortices is visible in Figure 6.10 (see Johnson, E., 2014 dissertation). The $\bar{V}$ velocities are slightly positive (or more weakly negative since we still have a pump induced negative current) from $0 < y/H < 4$ and negative from $4 < y/H < 8$, suggesting a surface convergence zone at $y/H = 4$. Additionally, $\bar{U}$ velocities are greatest at $y/H = 4$ and decrease slightly to the left and right of the center.
Figure 6.10: Mean surface velocity fields for the three flow cases without ridges. The top three velocity fields show $\overline{U}$ (cm/sec) and the bottom three show $\overline{V}$ (cm/sec), with increasing pump frequency going from left to right.

Surface convergence and divergence zones can be seen in Figure 6.11. The surface velocity fields show faster $\overline{U}$ velocities between the ridges and slower velocities over the ridges. Convergence zones are visible between the ridges as positive $\overline{V}$ velocities from the left converge with negative $\overline{V}$ velocities from the right. Similarly, divergence zones occur directly above the ridges.
Figure 6.11: Mean surface velocity fields for the three flow cases with N=10 ridges. The top three velocity fields show $U$ (cm/sec) and the bottom three show $V$ (cm/sec), with increasing pump frequency going from left to right.

Spatially averaged spanwise profiles of $U$ and $V$ for each flow case are shown in Figures 6.12 – 6.15. For the flow cases with ridges, $U$ has a maximum at the center of each trough ($y/H = 1, 3, 5,$ and $7$) and a minimum above each ridge ($y/H = 0, 2, 4, 6$ and $8$). Although most of our $V$ velocities are negative due to the weak transverse current, signatures of the counter-rotating vortices can be seen.
Figure 6.12: Spatially and temporally averaged spanwise surface velocity profiles of $\bar{U}$ (cm/sec) for the three flow cases without ridges.

Figure 6.13: Spatially and temporally averaged spanwise surface velocity profiles of $\bar{U}$ (cm/sec) for the three flow cases with $N=10$ ridges.
Figure 6.14: Spatially and temporally averaged spanwise surface velocity profiles of $\bar{V}$ (cm/sec) for the three flow cases without ridges.

Figure 6.15: Spatially and temporally averaged spanwise surface velocity profiles of $\bar{V}$ (cm/sec) for the three flow cases with $N=10$ ridges.
6.2.2 RMS Surface Turbulence Measurements and Spanwise Profiles

RMS turbulence values, $u_{rms}$ and $v_{rms}$, are calculated at each subwindow in our FOV. Both streamwise and transverse rms turbulence values increase with increasing mean streamwise velocity and are typically 5-10% of the mean streamwise velocity (Figure 6.16). The highest levels of turbulence are observed above the ridges in regions of upflow, while lower levels exist in the trough regions (Figure 6.17).

Figure 6.16: RMS surface turbulence fields for the three flow cases without ridges. The top three turbulence fields show $u_{rms}$ (cm/sec) and the bottom three show $v_{rms}$ (cm/sec), with increasing pump frequency going from left to right.
Figure 6.17: RMS surface turbulence fields for the three flow cases with $N=10$ ridges. The top three turbulence fields show $u_{\text{rms}}$ (cm/sec) and the bottom three show $v_{\text{rms}}$ (cm/sec), with increasing pump frequency going from left to right.

Spanwise profiles of spatially averaged turbulence intensities ($u_{\text{rms}}$ and $v_{\text{rms}}$, normalized by $\overline{U_s}$) are shown in Figures 6.18 - 6.21. Notably, the turbulence intensities in the cases with ridges reach higher values than those in the cases without ridges, specifically above the ridges. This increase in surface turbulence will influence the rate of gas transfer at the interface.
Figure 6.18: Spatially and temporally averaged spanwise surface turbulence intensity profiles of $u_{rms}/U_s$ for the three flow cases without ridges.

Figure 6.19: Spatially and temporally averaged spanwise surface turbulence intensity profiles of $u_{rms}/U_s$ for the three flow cases with $N=10$ ridges.
Figure 6.20: Spatially and temporally averaged spanwise surface turbulence intensity profiles of $v_{rms}/U_s$ for the three flow cases without ridges.

Figure 6.21: Spatially and temporally averaged spanwise surface turbulence intensity profiles of $v_{rms}/U_s$ for the three flow cases with $N=10$ ridges.
6.2.3 Mean Surface Divergence

The mean surface divergence, $\beta = \frac{d\bar{W}}{dz}$, is calculated at each subwindow in our FOV.

The surface divergence represents the vertical transport of fluid to and from the interface. We compare the spanwise mean surface divergence values between our flow cases with secondary flows and our control cases in Figure 6.22. This comparison shows enhanced positive vertical transport of fluid to the free surface over the ridges at regions of upflow ($\beta > 0$), and enhanced negative vertical transport for fluid away from the free surface in the troughs ($\beta < 0$) for the flow cases with secondary flows. The strength of the vertical transport is higher in the flows with counter-rotating vortices due to the constant renewal of fluid to the interface.

![Figure 6.22: Comparison of spanwise surface divergence, $\beta$.](image)

Figure 6.22: Comparison of spanwise surface divergence, $\beta$. 

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6.2.4 RMS Surface Divergence

From the time series of surface divergence, $\beta$, calculated at each subwindow in our FOV, we determine a surface divergence intensity (rms of surface divergence), $\beta'$, at each location (Figure 6.23). Streaks of high surface divergence are observed above the bars due to upwelling at divergence zones.

![RMS Surface Divergence](image1)

![RMS Surface Divergence](image2)

![RMS Surface Divergence](image3)

Figure 6.23: RMS surface divergence intensities. The top three figures show $\beta'$ for the flow cases without ridges, with increasing pump frequency going from left to right. The bottom three figures show $\beta'$ for the flow cases with $N=10$ ridges, with increasing pump frequency going from left to right.

We compare the spanwise mean rms surface divergence values between our flow cases with secondary flows and our control cases in Figure 6.24. We see enhanced rms surface divergence values for the flow cases with ridges. A spatial
average is used to compute a bulk mean surface divergence intensity, $\overline{\beta'}$, for each flow case (Table 7). $\overline{\beta'}$ is shown to increase with increasing flow rate. Importantly, $\overline{\beta'}$ is approximately one-and-a-half to two times larger in the flow cases with ridges than in the flow cases without.

Figure 6.24: Comparison of spanwise rms surface divergence, $\beta'$. 
Table 7: $\overline{\beta'}$ values for each flow case.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>$N_{\text{ridges}}$</th>
<th>$f_p$ (Hz)</th>
<th>$\overline{\beta'}$ (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.6</td>
<td>1.1</td>
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<td>5</td>
<td>10</td>
<td>2.8</td>
<td>3.0</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>4.9</td>
<td>5.2</td>
</tr>
</tbody>
</table>

6.2.5 Comparison of Bulk Flow Parameters

To easily compare the properties of the surface flow for each experimental case, we compute bulk spatial and temporal mean parameters (Table 8). Although $\overline{U}$ decreases slightly in flow cases with ridges due to additional drag and the upwelling of slow turbulent fluid caused by the ridges, $\overline{u_{rms}}$, $\overline{v_{rms}}$, and $\overline{\beta'}$ are higher for the cases with ridges. The increase in turbulence and surface divergence intensities lead to higher gas transfer velocities for the cases with ridges and will be discussed further in Section 6.3.
Table 8: Comparison of bulk flow parameters (\( \bar{U}_s \), \( \text{Re}_H \), \( \overline{u_{\text{rms}}} \), \( \overline{v_{\text{rms}}} \), and \( \bar{\beta}^1 \)) for flow cases with and without ridges.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>( N_{\text{ridges}} )</th>
<th>( f_p ) (Hz)</th>
<th>( \bar{U}_s ) (cm/sec)</th>
<th>( \text{Re}_H )</th>
<th>( \overline{u_{\text{rms}}} ) (cm/sec)</th>
<th>( \overline{v_{\text{rms}}} ) (cm/sec)</th>
<th>( \bar{\beta}^1 ) (1/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.6</td>
<td>17.6</td>
<td>18700</td>
<td>1.3</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>2.8</td>
<td>31.6</td>
<td>33600</td>
<td>2.2</td>
<td>1.2</td>
<td>1.8</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>4.9</td>
<td>56.3</td>
<td>58300</td>
<td>4.0</td>
<td>1.7</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>1.6</td>
<td>16.4</td>
<td>17500</td>
<td>1.4</td>
<td>0.9</td>
<td>1.8</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>2.8</td>
<td>29.7</td>
<td>31600</td>
<td>2.5</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>4.9</td>
<td>53.9</td>
<td>55900</td>
<td>4.8</td>
<td>2.3</td>
<td>5.2</td>
</tr>
</tbody>
</table>

6.2.6 Comparison of Pre-Processing Techniques

The background in our PIV images is a source of disturbance and can introduce unwanted noise. Pre-processing techniques have been developed to remove background noise while preserving the pixel intensity of the tracer particles. In order to remove the background from our PIV images, two different pre-processing schemes are investigated and utilized: a minimum pixel intensity method (Cowen and Monismith, 1997) and a background extraction method (Honkanen and Nobach, 2005).

The minimum pixel intensity method is ideal for removing a stationary background. The entire set of images is analyzed and a single minimum pixel intensity is determined for every pixel in the image area. A minimum pixel intensity image is created for the first images in the pairs of two, denoted “Background Image A”, and a
minimum pixel intensity for the second images in the pairs, “Background Image B”. These images are slightly different due to minor disparities in the two strobe flashes.

In the background extraction method, the second image in each pair is used as the reference image. The reference image is subtracted from the first image, removing the background noise at that point in time. Positive values are extracted and become the first image in the pair, and negative values are extracted, multiplied by -1, and used as the second image in the pair. The two images are then used in our PIV cross-correlation algorithm. The background extraction method uses a unique reference image for each image pair, thus accounting for time varying background reflections and noise caused by the uneven free surface.

The minimum pixel intensity method worked well for our flow cases without the ridges because the free surface was nearly flat and the background did not vary much throughout the series of images. Due to the regions of upflow and downflow, the free surface was more dynamic and energetic during the flow cases with ridges. The background extraction method worked best for these cases. Tables 8 and 9 compare the average percent of invalid vectors for both pre-processing techniques for the cases without ridges and with $N=10$ ridges, respectively. The chosen technique for each flow case is shown in red. Although the background extraction method used on the PIV images for the flow cases with ridges shows slightly higher values of invalid vectors, it was able to remove unwanted reflections and background noise that the minimum pixel intensity method did not. The background noise that was not removed by the background extraction method for the cases without ridges and the minimum pixel intensity method for the cases with ridges is shown in Figures 6.25 and 6.26.
Table 9: Average percent of invalid vectors in the raw results for each pre-processing technique for flow cases without ridges.

<table>
<thead>
<tr>
<th>Pre-processing Technique</th>
<th>$f_p = 1.6$ Hz</th>
<th>$f_p = 2.8$ Hz</th>
<th>$f_p = 4.9$ Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min-Pixel Intensity</td>
<td>0.6 %</td>
<td>0.2 %</td>
<td>0.8 %</td>
</tr>
<tr>
<td>Background Extraction</td>
<td>5.6 %</td>
<td>7.5 %</td>
<td>8.4 %</td>
</tr>
</tbody>
</table>

Table 10: Average percent of invalid vectors in the raw results for each pre-processing technique for flow cases with PVC ridges.

<table>
<thead>
<tr>
<th>Pre-processing Technique</th>
<th>$f_p = 1.6$ Hz</th>
<th>$f_p = 2.8$ Hz</th>
<th>$f_p = 4.9$ Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min-Pixel Intensity</td>
<td>1.5 %</td>
<td>1.1 %</td>
<td>3.3 %</td>
</tr>
<tr>
<td>Background Extraction</td>
<td>3.3 %</td>
<td>3.6 %</td>
<td>7.5 %</td>
</tr>
</tbody>
</table>
Figure 6.25: PIV images for flow cases without ridges. Images were pre-processed using the background extraction method and evidence of background noise exists. The minimum pixel intensity method was used for the PIV results shown and used in this research for these flow cases.
Figure 6.26: PIV images for flow cases with $N=10$ ridges. Images were pre-processed using the minimum pixel intensity method and evidence of background noise exists. The background extraction method was used for the PIV results shown and used in this research for these flow cases.

6.2.7 Post-processing Techniques

An AGW filter is applied to the temporal velocity data at each subwindow location in our PIV results (see Section 6.1.3 for a detailed description of the AGW filter). Tables 10 and 11 compare the average percent of invalid vectors after AGW filtering for flow cases with and without ridges for both pre-processing techniques. The minimum pixel intensity method has lower average percent of invalid vectors than the background intensity method for the flow cases without ridges. For the flow cases with $N=10$ ridges, the background extraction method has slightly higher average percent of
invalid vectors than the minimum pixel intensity method after being filtered. Again, this is because the background extraction method was able to remove unwanted background noise and reflections.

Table 11: Average percent of invalid vectors in the AGW filtered results for each pre-processing technique for flow cases without ridges.

<table>
<thead>
<tr>
<th>Pre-processing Technique</th>
<th>$f_p = 1.6$ Hz</th>
<th>$f_p = 2.8$ Hz</th>
<th>$f_p = 4.9$ Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min-Pixel Intensity</td>
<td>3.4 %</td>
<td>1.7 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>Background Extraction</td>
<td>6.8 %</td>
<td>7.6 %</td>
<td>8.5 %</td>
</tr>
</tbody>
</table>

Table 12: Average percent of invalid vectors in the AGW filtered results for each pre-processing technique for flow cases with PVC ridges.

<table>
<thead>
<tr>
<th>Pre-processing Technique</th>
<th>$f_p = 1.6$ Hz</th>
<th>$f_p = 2.8$ Hz</th>
<th>$f_p = 4.9$ Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min-Pixel Intensity</td>
<td>13.3 %</td>
<td>6.7 %</td>
<td>11.6 %</td>
</tr>
<tr>
<td>Background Extraction</td>
<td>11.1 %</td>
<td>8.8 %</td>
<td>15.2 %</td>
</tr>
</tbody>
</table>
6.3  Gas Transfer Measurements

6.3.1  Reaeration Curves and Gas Transfer Velocities

To determine the gas transfer velocity, \( k \), for each experimental flow case, we use a least squares approach to fit the exponential gas transfer model (Equation 14) to the reaeration curve obtained from our time series of DO measurements. The \( k \) value that gives the best fit to our experimental data is taken as the gas transfer velocity for a particular flow case (all \( R^2 \geq 0.975 \)). The results of our gas transfer experiments for each flow case are presented here.

Figure 6.27 shows the DO reaeration curves from our experimental data and best-fit exponential gas transfer models with corresponding \( k \) values for the three flow cases without ridges. As expected, \( k \) is shown to increase with increasing streamwise velocity because of the proportional increase in surface turbulence known to drive the gas transfer process.
Figure 6.27: Measured DO reaeration curves and best fit $k$ (cm/hr) values for three flow cases without ridges. Gas transfer velocity increases with increasing mean streamwise velocity.

Figure 6.28 shows the experimental DO data and the best-fit exponential gas transfer model for the three flow cases with $N=10$ ridges. Again, $k$ increases with increasing streamwise velocity.
Figure 6.28: Measured DO reaeration curves and best fit $k$ (cm/hr) values for three flow cases with $N=10$ ridges. Gas transfer velocity increases with increasing mean streamwise velocity.

The best-fit exponential gas transfer models and corresponding $k$ values for flow cases without ridges are compared to the flow cases with $N=10$ ridges in Figure 6.29. Detailed parameters for each gas transfer experiment, including $k$, are outlined in Table 12. Most significantly, the $k$ values are shown to be 10-15% higher for the flow cases with ridges than they are for the comparable flow cases without ridges. The increase in gas transfer velocity is caused by the increase in surface turbulence and divergence intensities for the cases with stabilized secondary flows. Our results confirm our hypothesis that counter-rotating vortices increase the direct air capture of $O_2$ at the interface, and that gas transfer is dependent on the strength of surface
divergence and turbulence at the interface (i.e., the rate that fresh water parcels are carried to the air-water interface). The counter-rotating vortices provide a constant source of upflow above the ridges. Highly turbulent fluid is transported to the interface in the regions of upflow. Simultaneously, the saturated parcels of water are transported away from the interface at regions of downflow. This process allows for fresh parcels to come in contact with the air, thus making the gas transfer process more efficient.

Figure 6.29: Comparison of DO curves and gas transfer velocities for three flow speeds for cases with and without ridges. The blue curves represent the flow cases without ridges and the red curves represent the flow cases with $N=10$ ridges (secondary flows).
Table 13: Gas transfer velocities, $k$ (cm/hr), for each experimental flow case.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>$N_{ridges}$</th>
<th>Re$_H$</th>
<th>$T_{water}$ (°C)</th>
<th>$k$ (cm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>18700</td>
<td>22.9</td>
<td>5.7</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>33600</td>
<td>22.7</td>
<td>10.3</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>58300</td>
<td>21.7</td>
<td>15.0</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>17500</td>
<td>22.8</td>
<td>6.6</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>31600</td>
<td>22.4</td>
<td>11.9</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>55900</td>
<td>21.8</td>
<td>16.4</td>
</tr>
</tbody>
</table>

Gas transfer velocity, $k$, is directly proportional to Re$_H$, as shown in Figure 6.30. The Reynold’s numbers for our flow cases with $N=10$ ridges are slightly lower than those for flow cases without ridges at the same pump frequencies due to slightly lower $\bar{U}$ values. Even at lower Reynold’s numbers, however, the $k$ values for the flow cases with ridges are significantly higher. This suggests that $k$ is influenced by the existence and physical nature of the secondary flows and is not solely dependent on Reynold’s number and increasing bulk turbulence.
6.3.2 Temperature Sensitivity

As discussed in Section 5.1.2, the saturation concentration of O$_2$ in water is dependent on water temperature, barometric pressure, and salinity. The water temperature, however, was shown to vary greatly depending on the time of year that an experiment took place. Our first round of gas transfer experiments with $N=10$ ridges was conducted in August, 2015. The average water temperature over the course of this set of experiments was 22.5 degrees C. The second set of experiments was conducted in January, 2016, and consisted of the flow cases without ridges. The average water temperature during the second set of experiments was 17.5 degrees C. After analyzing the data and finding inconsistent results, we realized that the gas transfer experiments are very temperature sensitive. Colder water holds higher concentrations of O$_2$. 

Figure 6.30: Comparison of $k$ (cm/sec) values as a function of Re for flow cases with and without ridges.
resulting in a higher potential for gas transfer and therefore higher $k$ values. We realized that in order to accurately compare the gas transfer results for the cases with and without ridges, all of the experiments had to be conducted at a constant water temperature.

The heating system in the DeFrees Laboratory was set to achieve constant average water temperatures of 22.5 degrees C for all of the flow cases both with, and without ridges. All of the data presented in Section 6.3.1 was collected at an approximately constant water temperature. Figure 6.31 compares the DO reaeration curves and corresponding $k$ values for the same flow cases conducted at two different water temperatures (cold and warm). As expected, experiments conducted with cold water show higher $k$ values than those conducted with warm water, as high as a 14% increase in $k$ for flow cases with a pump frequency of 4.9 Hz. Gas transfer velocities show a clear and significant dependence on water temperature. Water temperature should be carefully monitored and controlled in future gas transfer studies.
Figure 6.31: Comparison of DO reaeration curves and corresponding $k$ values at three flow speeds for experiments without ridges, conducted at different water temperatures (cold and warm). The average temperature during the cold water experiments was 17.5 degrees C and the average temperature during the warm water experiments was 22.5 degrees C.

6.4 Gas Transfer Model Comparisons

Our experimentally determined gas transfer velocities are compared to estimates from two models of gas transfer: a surface divergence model that depends on $\beta^t$ (McCready et al., 1986), and a model that combines surface divergence and surface renewal models that depends on the bulk surface velocity, $\overline{U}$ (Turney and Banerjee, 2013). Figures 6.32 and 6.33 show comparisons of our experimental $k$ results to the model predictions for the flow cases without ridges and with $N=10$ ridges, respectively. The Turney and Banerjee gas transfer model is shown to increasingly
underestimate $k$ with increasing Reynold’s number for both sets of flow cases. The McCready et al. gas transfer model overestimates $k$ for the flow cases with the lowest Reynold’s numbers and underestimates $k$ for the cases with the highest Reynold’s numbers. This model is able to predict $k$ for the flow cases with Reynold’s numbers around 32000 fairly well. The surface divergence model coefficient, $c$, that best fits our experimental $k$ values, is 0.5 for the flow cases without ridges, and 0.4 for the cases with N=10 ridges. These values correspond with typical values observed in open channel flows and flows with low-moderate wind (Turney and Banerjee, 2013).

Figure 6.32: Experimentally determined gas transfer velocity values for flow cases without ridges compared to $k$ estimates from two gas transfer models: surface renewal/divergence model (Turney and Banerjee, 2013) and surface divergence model (McCready et al., 1986).
Figure 6.33: Experimentally determined gas transfer velocity values for flow cases with \( N = 10 \) ridges compared to \( k \) estimates from two gas transfer models: surface renewal/divergence model (Turney and Banerjee, 2013) and surface divergence model (McCready et al., 1986).

### 6.5 Conclusion

We have confirmed that stabilized, counter-rotating vortices in open channel flows produce higher levels of surface turbulence, surface divergence, and rms surface divergence than flows without organized secondary flow structures. The highest levels of surface turbulence and rms surface divergence are observed above the ridges due to the upflow of slower, more turbulent fluid. This increase in the renewal of fresh water parcels to the free surface is shown to increase the gas transfer velocity of oxygen across the air-water interface by 9-15%.
Chapter 7

Future Work

This work has utilized state-of-the-art experimental techniques in the DeFrees Hydraulics Laboratory to investigate the effect of secondary flows on interfacial gas transfer of oxygen into water. Additional research is needed to determine the optimal ridge geometry and spacing that will increase the strength and stability of the counter-rotating vortices in the flow. Strategically placed roughness elements have the potential to strengthen the secondary flows and promote higher surface turbulence and divergence values. In addition, alternative, low-energy, hydro-mechanical methods for increasing gas transfer should be investigated and potentially coupled with the development of secondary flows for increased gas transfer efficiencies. For example, capillary waves are known to increase the interfacial air-water surface area of a particular fluid source (Zhang, 1995). Roughness elements placed on the side walls of the ponds could generate capillary waves, thus increasing gas transfer velocities. This optimization is needed to further enhance gas transfer velocities to improve the efficiency of algae raceway ponds.
Appendix A

Uncertainty Analysis

The uncertainty in a single sample measurement can be separated into two types: bias error and random error. The bias errors are fixed errors in an experiment and generally have a non-zero mean, with zero variance. Random errors, however, have zero mean with a non-zero variance. These two types of uncertainty can be estimated separately and combined to obtain a total uncertainty for a given measurement technique in a laboratory experiment.

Bias errors can be determined using the root-sum-square (RSS) technique (Kline and McClintock, 1953). In this method, we take the square root of the sum of all of the magnitudes of all of the possible error components in our measurements. Worst-case error estimates are used to characterize the bias error in the different variables in a given measurement. This combination of all possible bias errors gives an estimate of the bias error in a measurement. The source of bias error in our ADV measurements comes directly from the calibration of the instrument. The manufacturers report the accuracy of the Vectrino to be \( \pm 0.5\% \) of the measured velocity \( \pm 1 \) mm/s. This accuracy, along with the RSS technique, was used to determine the bias error in the mean velocities and turbulent fluctuations.

Our reported results from our PIV analysis have two sources of bias uncertainty. The spatial calibration of our images was used to calculate the displacement of a particle in pixels and convert it to cm (\( \Delta x \)). A bias error is also present in the timing system used to determine the time between images (\( \Delta t \)). This
procedure introduced a possible bias error in our calculations of velocity and turbulent fluctuations \((\text{velocity}=\Delta x / \Delta t)\). These bias errors are determined using the “worst-case” approach. The bias error in the \(\Delta x\) term was determined to be \(\pm 0.0385\) cm. The bias error in the \(\Delta t\) value was estimated at \(\pm 10^{-6}\) seconds, or 1 microsecond. The timing error is considered negligible because the spatial calibration error is orders of magnitude larger. The bias errors and the RSS technique were utilized to calculate the total bias error in our mean velocity, turbulent fluctuation calculations, and \(\beta'\).

Random error can be calculated directly from the sample record of data for each spatial location. The bootstrap technique is utilized to estimate the random error in a given measurement (Efron and Tibshirani, 1993). The 95% confidence interval is used to analyze the random error in our measurements. A resample number of 1000 is used for this analysis. A summary of the worst case (for all locations in space) 95% uncertainty interval estimates of our experimental measurements is shown in Table 13.
Table 14. Worst case 95% uncertainty bounds for experimental measurements.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>Measurement</th>
<th>Bias</th>
<th>Random</th>
<th>Total</th>
<th>% of measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ADV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 1.8</td>
<td>$\pm$ 0.3</td>
<td>$\pm$ 1.8</td>
<td>$\pm$ 1.2</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 4.5</td>
<td>$\pm$ 3.5</td>
<td>$\pm$ 8.8</td>
<td>$\pm$ 3.3</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{V}$ (mm/s)</td>
<td>$\pm$ 0.03</td>
<td>$\pm$ 0.02</td>
<td>$\pm$ 0.04</td>
<td>$\pm$ 3.2</td>
</tr>
<tr>
<td></td>
<td>PIV $u_{rms}$ (mm/s)</td>
<td>$\pm$ 0.3</td>
<td>$\pm$ 0.3</td>
<td>$\pm$ 0.6</td>
<td>$\pm$ 3.4</td>
</tr>
<tr>
<td></td>
<td>PIV $v_{rms}$ (mm/s)</td>
<td>$\pm$ 0.17</td>
<td>$\pm$ 0.2</td>
<td>$\pm$ 0.3</td>
<td>$\pm$ 4.2</td>
</tr>
<tr>
<td></td>
<td>$\beta'$ (1/sec)</td>
<td>$\pm$ 0.04</td>
<td>$\pm$ 0.03</td>
<td>$\pm$ 0.05</td>
<td>$\pm$ 4.5</td>
</tr>
<tr>
<td>2</td>
<td>ADV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 2.4</td>
<td>$\pm$ 0.5</td>
<td>$\pm$ 2.9</td>
<td>$\pm$ 0.9</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 8.2</td>
<td>$\pm$ 4.7</td>
<td>$\pm$ 13.0</td>
<td>$\pm$ 3.0</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{V}$ (mm/s)</td>
<td>$\pm$ 0.04</td>
<td>$\pm$ 0.04</td>
<td>$\pm$ 0.08</td>
<td>$\pm$ 3.5</td>
</tr>
<tr>
<td></td>
<td>PIV $u_{rms}$ (mm/s)</td>
<td>$\pm$ 0.5</td>
<td>$\pm$ 0.8</td>
<td>$\pm$ 1.3</td>
<td>$\pm$ 4.8</td>
</tr>
<tr>
<td></td>
<td>PIV $v_{rms}$ (mm/s)</td>
<td>$\pm$ 0.3</td>
<td>$\pm$ 0.5</td>
<td>$\pm$ 0.8</td>
<td>$\pm$ 5.2</td>
</tr>
<tr>
<td></td>
<td>$\beta'$ (1/sec)</td>
<td>$\pm$ 0.06</td>
<td>$\pm$ 0.07</td>
<td>$\pm$ 0.09</td>
<td>$\pm$ 5.2</td>
</tr>
<tr>
<td>3</td>
<td>ADV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 3.6</td>
<td>$\pm$ 0.8</td>
<td>$\pm$ 4.4</td>
<td>$\pm$ 0.7</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 14.6</td>
<td>$\pm$ 28.2</td>
<td>$\pm$ 42.8</td>
<td>$\pm$ 5.6</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{V}$ (mm/s)</td>
<td>$\pm$ 0.06</td>
<td>$\pm$ 0.08</td>
<td>$\pm$ 0.14</td>
<td>$\pm$ 4.2</td>
</tr>
<tr>
<td></td>
<td>PIV $u_{rms}$ (mm/s)</td>
<td>$\pm$ 1.0</td>
<td>$\pm$ 1.8</td>
<td>$\pm$ 2.8</td>
<td>$\pm$ 5.4</td>
</tr>
<tr>
<td></td>
<td>PIV $v_{rms}$ (mm/s)</td>
<td>$\pm$ 0.4</td>
<td>$\pm$ 0.9</td>
<td>$\pm$ 1.3</td>
<td>$\pm$ 6.3</td>
</tr>
<tr>
<td></td>
<td>$\beta'$ (1/sec)</td>
<td>$\pm$ 0.09</td>
<td>$\pm$ 0.11</td>
<td>$\pm$ 0.15</td>
<td>$\pm$ 5.6</td>
</tr>
<tr>
<td>4</td>
<td>ADV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 1.7</td>
<td>$\pm$ 0.2</td>
<td>$\pm$ 1.9</td>
<td>$\pm$ 1.2</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 4.2</td>
<td>$\pm$ 5.9</td>
<td>$\pm$ 10.1</td>
<td>$\pm$ 4.4</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{V}$ (mm/s)</td>
<td>$\pm$ 0.03</td>
<td>$\pm$ 0.03</td>
<td>$\pm$ 0.06</td>
<td>$\pm$ 3.5</td>
</tr>
<tr>
<td></td>
<td>PIV $u_{rms}$ (mm/s)</td>
<td>$\pm$ 0.4</td>
<td>$\pm$ 0.4</td>
<td>$\pm$ 0.8</td>
<td>$\pm$ 3.9</td>
</tr>
<tr>
<td></td>
<td>PIV $v_{rms}$ (mm/s)</td>
<td>$\pm$ 0.2</td>
<td>$\pm$ 0.2</td>
<td>$\pm$ 0.4</td>
<td>$\pm$ 3.7</td>
</tr>
<tr>
<td></td>
<td>$\beta'$ (1/sec)</td>
<td>$\pm$ 0.06</td>
<td>$\pm$ 0.07</td>
<td>$\pm$ 0.10</td>
<td>$\pm$ 5.3</td>
</tr>
<tr>
<td>5</td>
<td>ADV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 2.4</td>
<td>$\pm$ 0.6</td>
<td>$\pm$ 3.0</td>
<td>$\pm$ 0.9</td>
</tr>
<tr>
<td></td>
<td>PIV $\bar{U}$ (mm/s)</td>
<td>$\pm$ 7.7</td>
<td>$\pm$ 15.4</td>
<td>$\pm$ 23.1</td>
<td>$\pm$ 5.8</td>
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<td>PIV $\bar{V}$ (mm/s)</td>
<td>$\pm$ 0.06</td>
<td>$\pm$ 0.1</td>
<td>$\pm$ 0.16</td>
<td>$\pm$ 5.3</td>
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<td>PIV $u_{rms}$ (mm/s)</td>
<td>$\pm$ 0.6</td>
<td>$\pm$ 0.8</td>
<td>$\pm$ 1.4</td>
<td>$\pm$ 4.3</td>
</tr>
<tr>
<td></td>
<td>PIV $v_{rms}$ (mm/s)</td>
<td>$\pm$ 0.3</td>
<td>$\pm$ 0.4</td>
<td>$\pm$ 0.7</td>
<td>$\pm$ 4.7</td>
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<tr>
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<td>$\beta'$ (1/sec)</td>
<td>$\pm$ 0.10</td>
<td>$\pm$ 0.16</td>
<td>$\pm$ 0.19</td>
<td>$\pm$ 6.3</td>
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<tr>
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<td>ADV $\bar{U}$ (mm/s)</td>
<td>PIV $\bar{U}$ (mm/s)</td>
<td>PIV $\bar{V}$ (mm/s)</td>
<td>PIV $u_{rms}$ (mm/s)</td>
<td>PIV $v_{rms}$ (mm/s)</td>
</tr>
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<td>----------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td>± 3.4</td>
<td>± 13.9</td>
<td>± 0.1</td>
<td>± 1.0</td>
<td>± 0.5</td>
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<tr>
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<td>± 0.7</td>
<td>± 27.5</td>
<td>± 0.2</td>
<td>± 2.2</td>
<td>± 1.3</td>
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<tr>
<td></td>
<td>± 3.5</td>
<td>± 30.8</td>
<td>± 0.2</td>
<td>± 2.5</td>
<td>± 1.4</td>
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<td>± 0.7</td>
<td>± 5.7</td>
<td>± 5.5</td>
<td>± 6.2</td>
<td>± 6.8</td>
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</tbody>
</table>
Appendix B

Chemistry of Sodium Sulfite and Cobalt Chloride

The ASCE guidelines for measurement of oxygen in clean water require a value of 7.88 mg/L of sodium sulfite (Na$_2$SO$_3$) per 1.0 mg/L of DO concentration (with suggested excess of 20% to 250%), and a cobalt (Co) concentration between 0.10-0.50 mg/L as the catalyst in the deoxygenation reaction. Sodium sulfite amounts were calculated based on the assumption of fully saturated oxygen levels in the water at the beginning of the experiments. We used cobalt chloride hexahydrate (CoCl$_2$•6H$_2$O) as our catalyst, so stoichiometry was used to determine the required amounts needed to obtain the correct Co concentrations in our water. We were only required to add Co once at the start of a series of experiments, because the Co is a catalyst and therefore is not actually used up and removed during an experiment. The water was drained between the first three and second three experimental cases, so Co was added at the start of experiments 1 and 4. To be safe, we decided to use twice the minimum required amounts of CoCl$_2$•6H$_2$O. We used 30% excess Na$_2$SO$_3$ for each of the experiments. Chemical amounts for each experiment are shown in Table 14.
Table 15. Chemical amounts added for each experimental flow case.

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>H (m)</th>
<th>V (m$^3$)</th>
<th>CoCl$_2$•6H$_2$O (g)</th>
<th>Na$_2$SO$_3$ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.10</td>
<td>15.73</td>
<td>12.8</td>
<td>1456</td>
</tr>
<tr>
<td>2</td>
<td>0.10</td>
<td>15.73</td>
<td>0</td>
<td>1456</td>
</tr>
<tr>
<td>3</td>
<td>0.10</td>
<td>15.73</td>
<td>0</td>
<td>1456</td>
</tr>
<tr>
<td>4</td>
<td>0.10</td>
<td>15.58</td>
<td>12.8</td>
<td>1456</td>
</tr>
<tr>
<td>5</td>
<td>0.10</td>
<td>15.58</td>
<td>0</td>
<td>1456</td>
</tr>
<tr>
<td>6</td>
<td>0.10</td>
<td>15.58</td>
<td>0</td>
<td>1456</td>
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</table>
Appendix C

Barometric Pressure and Salinity Calculations

In order to confirm that the slight daily differences in barometric pressure have negligible effects on our calculations of $C_{DO_{sat}}$ used for the determination of $k$ in each of our gas transfer experiments, the daily average barometric pressure obtained from the meteorological station at the Ithaca Tompkins Regional Airport is reported in Table 16 (https://www.wunderground.com/). Corrections are made in the calculations of $C_{DO_{sat}}$ for each specific daily barometric pressure using the Benson and Krause (1984) empirical pressure factor. We determine the relative difference between the $C_{DO_{sat}}$ values that are corrected for barometric pressure differences to the $C_{DO_{sat}}$ values determined using a standard pressure of 1 atm. We confirm that the daily pressure differences amount to a relative difference of less than 1%. A 1% difference in $C_{DO_{sat}}$ will have a negligible effect on our $k$ values for each experiment, so a standard barometric pressure of 1 atm is used for all of our experiments.

Table 16. Daily Average Barometric Pressure (atm) and Relative Differences (%) in Calculated $C_{DO_{sat}}$ (mg/l)

<table>
<thead>
<tr>
<th>Experiment #</th>
<th>Date of Experiment</th>
<th>Daily Average Barometric Pressure (atm)</th>
<th>$C_{DO_{sat}}$ (mg/l) T=20 C</th>
<th>% Relative Difference in $C_{DO_{sat}}$ from 1 atm (Benson and Krause, 1984)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>02/29/16</td>
<td>0.993</td>
<td>9.026</td>
<td>0.731</td>
</tr>
<tr>
<td>2</td>
<td>03/01/16</td>
<td>0.994</td>
<td>9.040</td>
<td>0.580</td>
</tr>
<tr>
<td>3</td>
<td>03/03/16</td>
<td>1.009</td>
<td>9.177</td>
<td>0.934</td>
</tr>
<tr>
<td>4</td>
<td>03/07/16</td>
<td>1.005</td>
<td>9.108</td>
<td>0.173</td>
</tr>
<tr>
<td>5</td>
<td>03/08/16</td>
<td>1.005</td>
<td>9.141</td>
<td>0.530</td>
</tr>
<tr>
<td>6</td>
<td>03/10/16</td>
<td>1.001</td>
<td>9.104</td>
<td>0.126</td>
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</tbody>
</table>
The maximum possible salinity level in the water used in our experiments was 24 mg/l, or 24 ppm, taken from the maximum detected salinity level in the Cornell University Water System (Annual Drinking Water Quality Report, 2015). The Benson and Krause (1984) correction for salinity results in a less than 0.2% relative difference in $C_{DOsat}$ values calculated with the salinity correction and those calculated with a salinity of 0 mg/l. These extremely low levels of salinity have a negligible effect on our $C_{DOsat}$ and $k$ values, so a salinity of 0 mg/l is used for all calculations in this research.
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