Experimental Studies of Vertical Mixing Patterns in Open Channel Flow Generated by Two Delta Wings Side-by-Side

Garrett Vaughan
Utah State University

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EXPERIMENTAL STUDIES OF VERTICAL MIXING PATTERNS IN OPEN CHANNEL FLOW GENERATED BY TWO DELTA WINGS SIDE-BY-SIDE

by

Garrett Vaughan

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Mechanical Engineering

Approved:

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UTAH STATE UNIVERSITY
Logan, Utah

2013
Abstract

Experimental Studies of Vertical Mixing Patterns in Open Channel Flow Generated by Two Delta Wings Side-by-Side

by

Garrett Vaughan, Master of Science
Utah State University, 2013

Major Professor: Dr. Byard Wood
Department: Mechanical and Aerospace Engineering

Open channel raceway bioreactors are a low-cost system used to grow algae for biofuel production. Microalgae have many promises when it comes to renewable energy applications, but many economic hurdles must be overcome to achieve an economic fuel source that is competitive with petroleum-based fuels. One way to make algae more competitive is to improve vertical mixing in algae raceway bioreactors. Previous studies show that mixing may be increased by the addition of mechanisms such as airfoils. The circulation created helps move the algae from the bottom to top surface for necessary photosynthetic exchange. This improvement in light utilization allowed a certain study to achieve 2.2-2.4 times the amount of biomass relative to bioreactors without airfoils. This idea of increasing mixing in open channel raceways has been the focus of the Utah State University (USU) raceway hydraulics group.

Computational Fluid Dynamics (CFD), Acoustic Doppler Velocimetry (ADV), and Particle Image Velocimetry (PIV) are all methods used at USU to computationally and experimentally quantify mixing in an open channel raceway. They have also been used to observe the effects of using delta wings (DW) in increasing vertical mixing in the raceway. These efforts showed great potential in the DW in increasing vertical mixing in the open
channel bioreactor. However, this research begged the question, does the DW help increase algae growth? Three algae growth experiments comparing growth in a raceway with and without DW were completed. These experiments were successful, yielding an average 27.1% increase in the biomass. The DW appears to be a promising method of increasing algae biomass production.

The next important step was to quantify vertical mixing and understand flow patterns due to two DWs side-by-side. Raceway channels are wider as they increase in size; and arrays of DWs will need to be installed to achieve quality mixing throughout the bioreactor. Quality mixing was attained for several paddle wheel (PW) speeds. Also, an optimal spacing between the DWs in an array was found to be the width of the DW. This optimal spacing allows for the best increase in vertical mixing along the width of the channel. Dimensional analysis was performed using experimental data to estimate vertical mixing index (VMI) results for data obtained by larger scale DW experiments. This rough analysis showed that the VMI may be estimated from small to large scale within 26.6% and 26.5% when equating Reynolds and Froude numbers, respectively. These results suggest that quality mixing would still be present at a larger DW scale.
Public Abstract

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Utah State University, 2013

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Algae-derived biofuels is a hot topic of research interest when it comes to renewable energy applications. Algae can be grown in open systems that are low-cost, easy to maintain, and open to the environment. However, algae does not grow very dense in these systems. Mixing is an important factor in growing algae. If mixing were to be improved in open systems, the algae may be able to grow more dense. Certain studies show that placing a mechanical device such as an airfoil or airplane wing in the water will be able to increase the capability of mixing in the open system. One specific study showed an increase in the algae by 2.2-2.4 times. This is because the increased mixing allowed the algae to reach the top water surface and obtain much needed sunlight for improved growth.

Utah State University (USU) has used many methods to understand the mixing quality of a delta wing (DW) vortex generator. The DW helps to circulate the algae to the top water surface, like the airfoil, to help the algae grow. Many of the computational and experimental methods previously used focused on understanding the mixing patterns and mixing quality in the open system. However, experiments using a DW to grow algae were yet to be performed. Three algae growth experiments were completed and positive results
were obtained. The use of a DW to mix the algae and improve growth showed an overall 27% increase in the biomass.

Since the algae growth experiments were successful, it was important to understand the mixing quality and flow patterns of two DWs side-by-side. Experiments were created and performed to understand the patterns of mixing in the open system created by these two DWs in the water. The mixing quality was shown to be good and the best choice of how to space the DWs apart from each other was determined. Smaller scale DWs were used for these experiments, but using obtained data, mixing at a larger scale was estimated and showed quality mixing.
Acknowledgments

I am thankful for the opportunity to have taken on the challenge of completing a master’s degree in Mechanical Engineering. It feels like a great accomplishment to have completed a challenge as difficult as this. I have learned much through this experience and would not change the times of trial, stress, frustration, and success for anything.

This opportunity would not have been realized if it were not for the great faculty at Utah State University. I must especially thank Dr. Byard Wood who saw potential in me to do good work and complete the research at hand. If it weren’t for him, I would not have obtained the project I did. Although his schedule is busy, his advice and counsel have been excellent and really helped me learn and achieve great things.

I am very appreciative of Dr. Spall and his advice in performing the CFD simulations performed for this thesis. Also, I need to note the efforts of Ram Voleti and Blake Lance, for they paved the way with excellent studies and have helped me much throughout the completion of this research. Also, the efforts of Greg Townsley, Lihong Teng, and Justin Hunt cannot go unmentioned. They have been excellent help in performing the algae growth experiments and I could not have done it without them.

I also want to acknowledge my great family. They have always been there for me through the easiest and toughest of times. They have inspired me to work hard and to be my best self. Through their efforts I have learned to work hard, study hard, and play hard. Thanks for all you have done and continue to do for me!

Most importantly, I want to acknowledge my loving and supportive wife. Through the times I felt I could go no further, she helped to buoy me up and renew confidence in myself to keep moving forward. She never doubted, but was a great counselor and support to me without fail. Love you dear!

Garrett Vaughan
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>iii</td>
</tr>
<tr>
<td>Public Abstract</td>
<td>v</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>vii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>x</td>
</tr>
<tr>
<td>List of Figures</td>
<td>xi</td>
</tr>
<tr>
<td>Acronyms</td>
<td>xvii</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Literature Review</td>
<td>3</td>
</tr>
<tr>
<td>1.2.1 Open vs. Closed Systems</td>
<td>3</td>
</tr>
<tr>
<td>1.2.2 Light Utilization on Algae Growth</td>
<td>4</td>
</tr>
<tr>
<td>1.2.3 Mixing Effects on Algae</td>
<td>4</td>
</tr>
<tr>
<td>1.3 USU Research Efforts</td>
<td>6</td>
</tr>
<tr>
<td>1.4 Thesis Overview</td>
<td>9</td>
</tr>
<tr>
<td>2 Objectives</td>
<td>10</td>
</tr>
<tr>
<td>3 Experimental Methods</td>
<td>11</td>
</tr>
<tr>
<td>3.1 Algae Growth Experiments</td>
<td>11</td>
</tr>
<tr>
<td>3.2 SANT Raceway Hydraulic Experiments</td>
<td>14</td>
</tr>
<tr>
<td>3.2.1 Experimental Raceway</td>
<td>14</td>
</tr>
<tr>
<td>3.2.2 ADV Basics</td>
<td>15</td>
</tr>
<tr>
<td>3.2.3 ADV and PIV Preliminary Experiments</td>
<td>17</td>
</tr>
<tr>
<td>3.2.4 Downstream and Side Spacing</td>
<td>17</td>
</tr>
<tr>
<td>3.2.5 VMI</td>
<td>20</td>
</tr>
<tr>
<td>3.2.6 VMI Uncertainty Analysis</td>
<td>21</td>
</tr>
<tr>
<td>3.3 Cycle Time</td>
<td>23</td>
</tr>
<tr>
<td>3.4 Power Consumption Experiments</td>
<td>23</td>
</tr>
<tr>
<td>3.5 Dimensional Analysis</td>
<td>24</td>
</tr>
<tr>
<td>4 Results</td>
<td>26</td>
</tr>
<tr>
<td>4.1 Algae Growth Experiments</td>
<td>26</td>
</tr>
<tr>
<td>4.2 SANT Raceway Experiments</td>
<td>29</td>
</tr>
<tr>
<td>4.2.1 Downstream</td>
<td>29</td>
</tr>
<tr>
<td>4.2.2 Side Spacing</td>
<td>43</td>
</tr>
</tbody>
</table>
4.3 Power Consumption ................................................. 60
4.4 Dimensional Analysis Results ................................. 61

5 Conclusions and Future Recommendations ....................... 63

References ................................................................. 66

Appendices ................................................................. 68
   A Algae Growth Experiments ................................. 69
      A.1 Experimental Growth Data .......................... 69
   B ADV and PIV Preliminary Experiments .................. 74
      B.1 Experimental Data .................................. 74
   C CFD Vortex Dissipation Study ............................. 77
      C.1 Simulation Description ............................. 77
      C.2 Slip-Wall Approximation ........................... 78
      C.3 Free-Surface Approximation ....................... 83
   D Dimensional Analysis ......................................... 88
      D.1 Dimensional Analysis ............................... 88
## List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Algae growth experiment parameters</td>
<td>12</td>
</tr>
<tr>
<td>3.2</td>
<td>16-MHz MicroADV specifications</td>
<td>15</td>
</tr>
<tr>
<td>4.1</td>
<td>Peak-to-peak data comparison of algae growth experiments</td>
<td>29</td>
</tr>
<tr>
<td>4.2</td>
<td>VMI comparison of DW or no DW at location 1 ft in front of side-by-side DWs</td>
<td>41</td>
</tr>
<tr>
<td>4.3</td>
<td>Power data for PW speed vs. DW or no DW</td>
<td>60</td>
</tr>
<tr>
<td>4.4</td>
<td>Dimensional analysis to estimate $VMI_1$ from Eq. 3.11 (Reynolds number)</td>
<td>62</td>
</tr>
<tr>
<td>4.5</td>
<td>Dimensional analysis to estimate $VMI_1$ from Eq. 3.13 (Froude number)</td>
<td>62</td>
</tr>
<tr>
<td>A.1</td>
<td>Peak-to-peak data comparison of algae growth experiments</td>
<td>72</td>
</tr>
<tr>
<td>B.1</td>
<td>VMI comparison using PIV and ADV</td>
<td>74</td>
</tr>
<tr>
<td>B.2</td>
<td>Cycle time comparison using PIV and ADV</td>
<td>74</td>
</tr>
<tr>
<td>D.1</td>
<td>Side-by-side DW vertical velocity components</td>
<td>88</td>
</tr>
<tr>
<td>D.2</td>
<td>7.19 RPM vertical velocity and VMI data from [12]</td>
<td>88</td>
</tr>
<tr>
<td>D.3</td>
<td>Interpolated vertical velocity 2 and $VMI_2$ data for 22 RPM</td>
<td>89</td>
</tr>
</tbody>
</table>
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Placement of individual airfoils in foil array. Bottom figure represents positioning of array in the channel with D as the water depth and arrows indicating rotation of vortices. Figure from [8]</td>
<td>6</td>
</tr>
<tr>
<td>3.1</td>
<td>USU Research Greenhouse Facility: (left) outside greenhouse, (right) inside greenhouse</td>
<td>12</td>
</tr>
<tr>
<td>3.2</td>
<td>(left) Deep raceway with DWs installed, (right) cross-sectional dimensions of DW relative to raceway channel</td>
<td>13</td>
</tr>
<tr>
<td>3.3</td>
<td>Clear acrylic experimental raceway used for flow measurement studies</td>
<td>14</td>
</tr>
<tr>
<td>3.4</td>
<td>Diagram of ADV including transmitter, receivers, and sampling region. Figure from [13]</td>
<td>16</td>
</tr>
<tr>
<td>3.5</td>
<td>Test matrix diagram for downstream DW side-by-side experiments: 1) PW 2) DWs 3) flow straightener</td>
<td>18</td>
</tr>
<tr>
<td>3.6</td>
<td>5 x 18 grid setup for ADV data acquisition</td>
<td>18</td>
</tr>
<tr>
<td>3.7</td>
<td>Schematic of DW setup for downstream experiments</td>
<td>19</td>
</tr>
<tr>
<td>3.8</td>
<td>Test matrix diagram for side spacing DW side-by-side experiments: 1) PW 2) DWs 3) flow straightener</td>
<td>19</td>
</tr>
<tr>
<td>3.9</td>
<td>5 x 19 grid setup for ADV data acquisition</td>
<td>19</td>
</tr>
<tr>
<td>3.10</td>
<td>Schematic of DW setup for side spacing experiments</td>
<td>20</td>
</tr>
<tr>
<td>4.1</td>
<td>(left) Raceway with DWs, (right) Raceway without DWs</td>
<td>26</td>
</tr>
<tr>
<td>4.2</td>
<td>(left) Raceway with DWs, (right) Raceway without DWs</td>
<td>27</td>
</tr>
<tr>
<td>4.3</td>
<td>Dry weight data of DW vs. no DW algae growth for experiment 1. Values reported within 0.8% measurement uncertainty</td>
<td>27</td>
</tr>
<tr>
<td>4.4</td>
<td>Dry weight data of DW vs. no DW algae growth for experiment 2. Values reported within 0.8% measurement uncertainty</td>
<td>28</td>
</tr>
</tbody>
</table>
4.5 Dry weight data of DW vs. no DW algae growth for experiment 3. Values reported within 0.8% measurement uncertainty

4.6 In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 8 RPM

4.7 In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 8 RPM

4.8 In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 8 RPM

4.9 In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 8 RPM

4.10 In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 8 RPM

4.11 In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 10 RPM

4.12 In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 10 RPM

4.13 In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 10 RPM

4.14 In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 10 RPM

4.15 In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 10 RPM

4.16 In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 12 RPM

4.17 In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 12 RPM

4.18 In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 12 RPM

4.19 In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 12 RPM

4.20 In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 12 RPM
4.21 In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 14 RPM ........................................ 38
4.22 In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 14 RPM ................................................................. 38
4.23 In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 14 RPM ................................................................. 39
4.24 In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 14 RPM ................................................................. 39
4.25 In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 14 RPM ................................................................. 40
4.26 (left) Downstream experiment ADV and side-by-side DW setup, (right) stagnation line in channel center created by the DW vortices ................. 41
4.27 Downstream distance experiment VMI results relative to the side-by-side DW location ................................................................. 42
4.28 Downstream distance experiment cycle time results relative to side-by-side DW location ................................................................. 43
4.29 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 0.5 in. laterally ................................................................. 44
4.30 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 0.5 in. laterally ................................................................. 45
4.31 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 0.5 in. laterally ................................................................. 45
4.32 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 1.5 in. laterally ................................................................. 46
4.33 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 1.5 in. laterally ................................................................. 46
4.34 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 1.5 in. laterally ................................................................. 47
4.35 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 2.5 in. laterally ................................................................. 47
4.36 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 2.5 in. laterally ................................................................. 48
4.37 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 2.5 in. laterally ............................................................. 48
4.38 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 3.5 in. laterally ............................................................. 49
4.39 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 3.5 in. laterally ............................................................. 49
4.40 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 3.5 in. laterally ............................................................. 50
4.41 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 4.5 in. laterally ............................................................. 50
4.42 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 4.5 in. laterally ............................................................. 51
4.43 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 4.5 in. laterally ............................................................. 51
4.44 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 5.5 in. laterally ............................................................. 52
4.45 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 5.5 in. laterally ............................................................. 52
4.46 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 5.5 in. laterally ............................................................. 53
4.47 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 6.5 in. laterally ............................................................. 53
4.48 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 6.5 in. laterally ............................................................. 54
4.49 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 6.5 in. laterally ............................................................. 54
4.50 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 7.5 in. laterally ............................................................. 55
4.51 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 7.5 in. laterally ............................................................. 55
4.52 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 7.5 in. laterally ............................................................. 56
4.53 In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 8.5 in. laterally ......................................................... 56

4.54 In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 8.5 in. laterally ......................................................... 57

4.55 In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 8.5 in. laterally ......................................................... 57

4.56 Side spacing VMI results relative to downstream locations of side-by-side DWs 59

4.57 (left) 0.5 in. lateral side spacing of DWs front view, (right) downstream view of stagnation line created by 0.5 in. side spacing of DWs ................. 59

4.58 Side spacing cycle time results relative to the lateral spacing of side-by-side DWs ................................................................. 61

A.1 95% confidence interval from t-test on mean of algae growth experiments . 70

A.2 90% confidence interval from t-test on mean of algae growth experiments . 71

A.3 80% confidence interval from t-test on mean of algae growth experiments . 71

A.4 Normalized dry weight values for DW relative to peak dry weight values for no DW ................................................................. 73

B.1 In-plane velocity vector field obtained at 1.5 ft downstream of the DW for a PW speed of 20 Hz using PIV ......................................................... 75

B.2 In-plane velocity vector field obtained at 2.5 ft downstream of the DW for a PW speed of 20 Hz using PIV ......................................................... 75

B.3 In-plane velocity vector field obtained at 1.5 ft downstream of the DW for a PW speed of 20 Hz using ADV ......................................................... 76

B.4 In-plane velocity vector field obtained at 2.5 ft downstream of the DW for a PW speed of 20 Hz using ADV ......................................................... 76

C.1 CFD DW simulation showing streamlines of fluid motion ..................... 77

C.2 Magnitude of velocity in channel with respect to increasing water depth for a slip-wall boundary condition ............................................. 78

C.3 Dissipation rate of DW vortices with respect to increasing water depth for a slip-wall boundary condition ............................................. 79

C.4 CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 9.5 in. water depth ......................................................... 79
C.5 CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 10 in. water depth .................................................... 80
C.6 CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 11 in. water depth .................................................... 80
C.7 CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 12 in. water depth .................................................... 81
C.8 CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 13 in. water depth .................................................... 81
C.9 CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 14 in. water depth .................................................... 82
C.10 CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 15 in. water depth .................................................... 82
C.11 Magnitude of velocity in channel with respect to increasing water depth for a free-surface boundary condition ........................................... 83
C.12 Dissipation rate of DW vortices with respect to increasing water depth for a free-surface boundary condition ........................................... 84
C.13 CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 9.5 in. water depth ............................................... 84
C.14 CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 10 in. water depth ............................................... 85
C.15 CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 11 in. water depth ............................................... 85
C.16 CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 12 in. water depth ............................................... 86
C.17 CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 13 in. water depth ............................................... 86
C.18 CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 14 in. water depth ............................................... 87
C.19 CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 15 in. water depth ............................................... 87
D.1 Excel work of the dimensional analysis equating Reynolds numbers .......... 89
D.2 Excel work of the dimensional analysis equating Froude numbers .......... 90
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADV</td>
<td>Acoustic Doppler Velocimeter</td>
</tr>
<tr>
<td>ASP</td>
<td>Aquatic Species Program</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>DW</td>
<td>Delta Wing</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>PW</td>
<td>Paddle wheel</td>
</tr>
<tr>
<td>USU</td>
<td>Utah State University</td>
</tr>
<tr>
<td>VFD</td>
<td>Variable Frequency Drive</td>
</tr>
<tr>
<td>VMI</td>
<td>Vertical Mixing Index</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

Microalgae, further referred to as algae, is an on-going topic of research interest for renewable energy applications. The potential and promises of algae derived biofuels and other by-products are great, but the economic challenges are difficult to overcome [1–3]. At Utah State University (USU), research projects tailored to increasing algal biomass production are underway. In the Energy Systems Laboratory of the Mechanical and Aerospace Engineering Department, delta wings (DW) are being used to increase vertical mixing in open channel raceway ponds in hopes to increase biomass production and better raceway design. To better understand the purpose of this research and its state-of-art, this chapter will include the following: an overview of algae research importance, a Literature review, USU research efforts and DW state-of-art, and an overview of the thesis contents. By reviewing these sections, the motivation and importance of this work will be understood.

1.1 Background

For many years, research to use algae as an alternative energy resource has been and continues to be performed. In fact, over 30 years ago the Department of Energy (DOE) initiated a program called the Aquatic Species Program (ASP) for research and development of algal biofuels [1]. Through the ASP, many advances were made. These advances include algal strain isolation and characterization, studies of algal physiology and biochemistry, genetic engineering, engineering and process development, and outdoor demonstration-scale algal mass culture [1]. Although the ASP produced these many great advances, federal funding being low and the cost of petroleum being low decreased the need for further research and the program was dropped.

In recent years, interest of private investors, industries, and increasing interest of federal
agencies in algal biofuel research is on the rise and in search of cost-effective solutions as the world faces a high energy life-style. The demand is so great that 60% of US petroleum is imported and two-thirds of it is used for transportation [1]. Also, there is a growing concern on world economies and human life-styles due to increasing greenhouse gas emission. The potential to reduce such demand and greenhouse gas emission is great when considering renewable energy resources. However, many hurdles such as scalability, system viability, and production costs need to be overcome in order to compete with the current petroleum-based fuels. Due to the newer efforts in areas of academia, industry, and national laboratories, advanced biofuels that fit the needs of the world economy have great potential to be realized.

Although the current research to obtain an economic solution to algal based biofuels is not yet realized, many great advantages of algal based biofuels keep the research pushing forward. According to Pienkos and Darzins at the National Renewable Energy Laboratory (NREL), algae have six main advantages that include: high per-acre productivity, feedstock based on non-food resource, use of nonproductive or non-arable land, utilization of a wide variety of water sources, mitigation of greenhouse gas emission into the atmosphere, and production of both biofuels and valuable co-products [1]. Also, Singh and Gu state the following advantages of algae: year-round production, rapid growth potential, numerous species have oil content in 20-50% dry weight range, less water than terrestrial crops necessary for growth, aid in bio-fixation of waste CO₂, and production of co-products such as proteins and residual biomass, which may be used as a feed or fertilizer [2]. All-in-all, as research is pushed toward obtaining a system to use all these advantages in a cost-effective way, it is important to understand the current methods of algae production.

In order to understand the current methods of algae production, a literature review was conducted to understand both open and closed systems, light utilization in algae growth, and the effects of mixing on algae.
1.2 Literature Review

1.2.1 Open vs. Closed Systems

Among the methods of biomass and lipid production, there are two main systems that face great debate in effectiveness when cost, biomass growth, and lipid yield are concerned. Algae are either grown in an open or closed system. Fairly self-explanatory, an open system is a system that is not enclosed and has a surface that is exposed to the environment. A closed system is enclosed, such as in a clear tube, and still allows photosynthetic exchange. According to Li and Wan at Ohio State University, algae can be cultivated in low cost production systems such as open ponds. This system is operated in a continuous mode with a fixed supply of culture media, water, and nutrients. Contamination is the main risk of open systems. Cultivating algae in an enclosed bioreactor, in which the system is strictly controlled and no contamination occurs, is an alternative to overcome the problems with open systems. However, the high investment and operating costs are the main problem for the enclosed bioreactor [3].

Singh and Gu state that closed pond systems are similar to open ponds, but are covered for cooler climates. The open pond system requires constant 15°C temperatures, less maintenance, is less expensive to set-up but does produce lower yields [2]. Richmond and Qiang add that for open raceways low yields of algal mass are obtained and they require handling very large amounts of algal suspension, which often become readily contaminated as well as increasing cost of harvesting [4]. Pienkos and Darzins state that closed photobioreactors are more expensive to construct and are not a mature technology. Cultivation issues are present for both types of system, such as reactor construction materials, mixing, optimal cultivation scale, heating/cooling, evaporation, O₂ build-up, and CO₂ administration, have been considered and explored [1]. Although each system has its pros and cons, a clear best-solution continues to be under debate. The fact is both systems work and need to be matured in technology.

After algae have been produced in either an open or closed system, the next step is harvesting the biomass and preparing for conversion to biofuels and other co-products.
Pienkos and Darzins note from Guden and Thepenier that harvesting can account for an estimated 20-30% of the total production cost [1]. A main method to harvest algae, which is also the most expensive process, is centrifugation. Other methods to harvest and extract the oils include cross-flow filtering and even wet-extraction using solvents [1–3,5].

1.2.2 Light Utilization on Algae Growth

In order to increase biomass productivity it may be important to understand photosynthetic efficiency or light utilization in algae growth. Richmond and Qiang suggest that a paddle wheel (PW) alone is a poor device for light utilization that cannot practically create necessary high frequency of the dark/light cycle for light limited algal cells [4]. They performed growth experiments using a flat plate bioreactor where they used 1500 W halogen growth lamps, varying the distance to the reactor, to observe the effects of light intensity on algal growth. They noted that as light intensity increased, along with an increase in mixing that would not damage the cells, the algal biomass density increased. They note that the light-dark cycles to which the algal cells are exposed are a function of the intensity of light or lightpath, as well as the extent of turbulence to move the algal cells from the lit to dark volume of the reactor [4].

In the works of Carvalho et al., they state that light is necessary for algal photosynthesis, yet excessive or insufficient incident light constrains optimal performance. They outline the following three areas of importance when dealing with light utilization: (1) a light-limited region where photosynthetic efficiency increases with increasing irradiance; (2) a light-saturation area, in which photosynthetic capacities attain a maximum in the culture; (3) a photo-inhibition region, in which increases in light intensity become injurious to the cells [6]. These areas are important to understand because as the rate of photon absorption exceeds the rate at which photosynthesis can occur, 50-80% of the absorbed photons may be wasted and cause a reduction in solar conversion efficiency and cellular productivity [6].

1.2.3 Mixing Effects on Algae

As stated previously, when cultivating algae, one of the issues that is faced is producing
proper mixing in the system. Stagnant water does not sustain algal growth through its typical growth cycle and will not produce the maximum potential yield. Open systems typically have a PW to push the water along its channels where some mixing is created at the paddle and the bends of a conventional raceway due to secondary flow phenomena. Also, the steady or laminar flow aids the algae in sustaining its growth. Open systems do not produce the same yield as closed systems, but closed systems still need mixing which is typically created by bubbling CO$_2$ through the tube bioreactors. It is said that closed systems produce a higher yield, but at a much higher expense. Hence, mixing is necessary to sustain growth in either system, but does too much mixing hurt the algal growth? Depending on the species, Sullivan and Swift found the effects of small-scale turbulence to increase, decrease, or have no effect on growth [7]. Selection of the correct system and algal strain appear extremely important.

Laws et al. performed experiments to improve vertical mixing in open channel flow using airfoils. They state that efficiency of light utilization by phytoplankton can be markedly increased by exposing the cells to alternating periods of light and dark [8]. Thus each airfoil placed in the flow, where the width of the airfoil and depth of the water were equal, created two vortices circulating the water and cells from bottom to top. The setup of their experiments is shown in Fig. 1.1.

This circulation allowed the cells to reach the surface for the needed photosynthetic exchange. According to their results, the foil arrays were used to grow an experimental culture of P. tricornutum which lead to an increase 2.2-2.4 times the control with no foil arrays [8].

Another notable study was performed by Cheng and Dugan. What they did was take rectangular and triangular plates and placed them in water flow at an angle of attack to induce mixing. This is similar to Laws et al., except they did not use these shapes to observe the effects on algae growth. Their goal was to determine mixing relationships created by these various shapes so that the lowest energy expenditure could be achieved for the greatest amount of mixing and turbulence [9].
Throughout all experiments they were able to observe that a desirable fluid mixing zone was created downstream of the plates. They suggested with the observed mixing that a spacing of 4.5 m between downstream rows of plates should provide sufficient turbulence conditions. They also noted that the drag force on the plate was relatively insignificant regardless the plate shape or angle of attack [9]. With drag force directly affecting the power needed to move the water at a desired velocity, it is surprising they say this force is insignificant. They conclude similarly to Laws et al. that the best mixing observed was when the plates were spaced the width of the plate apart.

1.3 USU Research Efforts

From the literature review, the idea of increasing vertical mixing to better light utilization became the main focus of the USU raceway hydraulics group. It is apparent that
if a low-cost system, such as an open system, were to have an increase of mixing within the channel flow, an increase in biomass production could result. At USU, both computational and experimental tools have been used in improving algal raceway hydrodynamics for this purpose. These include Computational Fluid Dynamics (CFD), Acoustic Doppler Velocimeter (ADV), and Particle Image Velocimetry (PIV). Each measurement technique provided better understanding of the mixing quality of the open channel raceway, as well as the increase of mixing quality due to the DW. A brief explanation of the completed work for CFD, ADV, and PIV efforts will be given. These efforts set a strong foundation for the research that is to be expounded upon in this thesis.

Aaron Godfrey utilized CFD in observing the vertical mixing effects of DW in open channel flow. Through his studies, he was able to conclude that for meaningful increases in vertical mixing a series of DW is required. Understanding that DW can increase vertical mixing, he also notes that both spacing and angle of attack played a role in the levels of mixing attained. This alludes to the idea of optimal spacing and angle of attack of the DW. He also observed the turbulence effects on algal cells within his literature search whereupon he found that one must be selective in the algae species when increasing the levels of turbulence with DW. The reason is that certain algae species benefit from increased turbulence, whereas others show decrease in growth [10].

Ram Voleti focused his research efforts on constructing an acrylic raceway to be used for ADV measurement experiments. Also, the fact it was built out of acrylic allowed for PIV experiments to be performed. The main purpose was to provide experimental results to quantify the vertical mixing qualities of the DW, as well as understand the basic hydrodynamic characteristics of the open channel raceway. Voleti did this by quantifying the vertical mixing index (VMI) [11].

The VMI was used to quantify the vertical mixing behavior in the raceway [11]. VMI helps to understand the difference in mixing quality when comparing flow measurements with and without the DW. Due to the vortices created by the DW, the vertical velocity components tend to cancel each other out when summed together. Thus this normalized
parameter was formed, as shown in Eq. 1.1, with the velocity components of interest further outlined in Eq. 1.2 and 1.3.

\[ VMI = \frac{W}{U} \]  \quad (1.1)

\[ W = \frac{\sum_{i=1}^{n} |w_i|}{n} \]  \quad (1.2)

\[ U = \frac{\sum_{i=1}^{n} u_i}{n} \]  \quad (1.3)

The components of the equation are described as follows, \( n \) is the number of grid points, \( i \) is a single grid point, \(|w|\) is the absolute value of the vertical velocity component at each grid point, \( W \) is the average of the absolute value of the vertical velocities, and \( U \) is the average streamwise velocity at the plane of interest. When multiplied by 100, VMI may be represented as a percentage. A VMI of 0% would represent zero mixing within the flow. Anything above this would show that some form of mixing is present [11].

Voleti’s results confirm that the DW in the raceway shows a great influence of vertical mixing compared to the normal raceway without DW. Not only did the DW increase mixing, he also found that the vortices propagated downstream up to 3 m before returning to regular raceway conditions. For larger raceways; however, one DW would not suffice and he suggests spacing the DW 3 m or less apart to achieve good mixing throughout the raceway [11].

Blake Lance utilized the acrylic raceway to perform stereo PIV measurements to quantify and optimize mixing in the raceway using the DW. Through this comprehensive study, he was able to optimize the angle of attack and DW downstream distance spacing parameters. He found that an angle of attack of 40° and spacing of 65 in from one DW to the next would provide quality mixing in an economic fashion [12].

Lance also derived a basic flow mixing parameter called cycle time. Since VMI does not relate time to the algal circulation, cycle time was a new defined parameter. According to Lance, the algal cells have to cycle from the bottom to the top (or within 1-2 in to absorb
photons from the incident radiation), and back down again to complete their cycle [12]. Equation 1.4 shows the expression of cycle time required to quantify the algal circulation. $D$ is the water depth, $\sum_{i=1}^{n} |w_i|/n$ is the average velocity, and $\Delta t$ is the cycle time.

$$\Delta t = \frac{2D}{\sum_{i=1}^{n} |w_i|/n} \quad (1.4)$$

Each study showed great results that support the DW as a simple tool to increase the vertical mixing in open channel raceways. However, the studies performed to quantify the mixing quality and optimize the operational parameters of the DW begged a single question, does the DW help increase algal biomass production? Also, they all involved studies of a single DW in the flow. As the raceway channel width increases, the DW will have to be put in arrays. Understanding the information obtained from each previous study aided in the completion of the work contained in this thesis.

1.4 Thesis Overview

The research efforts of USU is pushing along for an idea to help improve the design of open channel raceways. Although much research has been done with the DW, does it even help increase the biomass production? If so, what is the next step to understand? The contents of this thesis include the answers to these questions along with the overall results of the objectives outlined in Chapter 2.
Chapter 2

Objectives

The purpose of this thesis work is to perform follow-up research for the USU Bioenergy Center aimed at increasing algal biomass for biofuel production. It is understood how to grow algae, but these efforts are underway to understand how to increase the algal growth process. The objectives for this work are outlined as follows:

- Conduct preliminary algal growth experiments using DW in open channel raceways to observe effects of mixing on algal biomass production
- Conduct ADV experiments with two DWs side-by-side to observe flow interaction of vortex generation and evaluate quality of mixing
- Conduct power consumption experiments to understand power requirements of side-by-side DWs
- Include preliminary PIV data in an Appendix
- Include CFD vortex dissipation study results in an Appendix
Chapter 3
Experimental Methods

This chapter outlines the experimental methods used to meet the outlined research objectives.

3.1 Algae Growth Experiments

As alluded to by the studies of Voleti, Godfrey, and Lance [10–12], the purpose of this study was to perform preliminary algae growth experiments in professionally manufactured open channel raceways to observe the biomass production affected by the DW. It is the understanding that conventional raceways have long straight channel sections that experience a state or uniform flow with low levels of mixing. This phenomena could lead to the settling of algae to the channel floor, preventing them from receiving much needed sunlight at the free surface. The addition of a DW will increase the vertical mixing in these uniform flow regions and circulate the algae from the bottom to the top free surface for necessary photosynthetic exchange. However, does the addition of the DW in these uniform flow regions have a positive or negative effect on algae growth?

The algae growth experiments were conducted in the research greenhouse at the Solar BioInnovations Center located on the USU Innovation Campus, as shown in Fig. 3.1. This environment allowed operation of well-controlled experiments in an enclosed greenhouse to minimize effects of contamination to the algae species being grown. An inside view of the greenhouse is also shown in Fig. 3.1 with a growth experiment underway.

Two professionally manufactured raceways were used for side-by-side comparison of the algal growth. One raceway contained three DWs and the other did not have the DWs. Sodium growth lamps were used on a 12 hour cycle to simulate summer growing conditions. Being near the end of the summer, the greenhouse temperatures experienced a wide range
as shown in Table 3.1. This large temperature fluctuation was a concern since the algae growth rate was considered best at room temperature. Fortunately, the facility had a chilling system that was used to regulate the raceway water temperature via cooling coils to balance these wide temperature variations.

Three growth experiments were completed with the two raceways oriented to north and south of each other in the greenhouse. The first two experiments were performed with the south raceway containing the DWs. To make sure there was no bias present between raceways, the third experiment was performed with the DWs in the north raceway. Table 3.1 shows the parameters that were maintained during the duration of these experiments.

Table 3.1: Algae growth experiment parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse Temperature Range</td>
<td>60 – 100°F</td>
</tr>
<tr>
<td>Raceway Water Temperature Range</td>
<td>70 – 75°F</td>
</tr>
<tr>
<td>Raceway Water Depth</td>
<td>10 in</td>
</tr>
<tr>
<td>Average Velocity of Water</td>
<td>0.82 ft/s</td>
</tr>
<tr>
<td>Number of DWs</td>
<td>3</td>
</tr>
<tr>
<td>DW Spacing</td>
<td>1.5 ft, 2.5 ft, 2.5 ft</td>
</tr>
<tr>
<td>Algae Strain</td>
<td><em>Chlorella Vulgaris</em></td>
</tr>
</tbody>
</table>

Note that the DW spacing is 1.5 ft from the raceway bend and then 2.5 ft to each DW after that. Hence, the DWs were spaced equidistant from one another as shown in Fig 3.2.
The DWs were also set in the flow at a 40° angle of attack.

![Fig. 3.2: (left) Deep raceway with DWs installed, (right) cross-sectional dimensions of DW relative to raceway channel](image)

It is also very important to note that the raceway geometry and dimensions were very different than the raceway used to observe DW vertical mixing for the experiments of Voleti and Lance [11, 12]. A simple cross sectional diagram in Fig. 3.2 shows the position of the DW with respect to the water depth. The trapezoid shaped channel proved to be difficult in choosing a best DW fit for the experiments.

As a basis for DW fabrication, a central location within the 10 in. depth was chosen for placement of the DW. Along with an arbitrary suggestion from Ram to make the DW fill 80% of the channel width, the placement in the channel led to a DW width of 6 in. Changing the aspect ratio was considered in fabrication in order to fill more of the channel flow, but this change would weaken the vortex effects and was avoided. Hence, the DW and channel were not a best fit in dimensions for the experiments.

Given the DW and channel dimensions, the water level was approximated to 4 in. below the DW and 3 in. above the DW. Ideally, the raceway would have side walls perpendicular to the raceway floor, unlike the trapezoid shape of the raceways used. This would have allowed for a better sized DW for the channel. Although there were some dimensional
issues to overcome in the setup of this experiment, best judgement was made to utilize the channel space and provide DWs that would induce vertical mixing.

As the experiments were run, through the efforts of Justin Hunt and Greg Townsley, dry weight measurements (g/L) for both raceways were obtained to observe the biomass growth rate over the life cycle of the algae. As a preliminary experiment, the main focus was to observe the DW effects on algae biomass productivity. Therefore, other measurements were not taken during these experiments.

3.2 SANT Raceway Hydraulic Experiments

3.2.1 Experimental Raceway

An acrylic raceway was used for the flow visualization studies outlined in the objectives. This raceway, located in the USU Energy Systems lab, was also used for the studies of Voleti and Lance [11,12]. As outlined previously by Voleti, the open channel is rectangular in shape with dimensions of 6.1 m in length, 0.44 m in width (of single channel), and 0.61 m in depth [11]. Figure 3.3 shows an image of the experimental raceway.

![Fig. 3.3: Clear acrylic experimental raceway used for flow measurement studies](image)

The raceway uses an Emerson Commander SK Variable Frequency Drive (VFD) to set
the PW to a desired speed for testing. The PW pushes the water around the raceway to simulate operating conditions of an open channel algae bioreactor. Due to the clear acrylic, flow visualization studies using ADV and PIV are possible. For this thesis, ADV was the main instrument used in data acquisition. The raceway contains a unistrut rail system used to slide the ADV probe to the desired plane of interest. The ADV could then be locked in place in order to sweep through the specified grid system for the experiment.

More details related to the specifications of the raceway may be found in Voleti’s thesis [11].

### 3.2.2 ADV Basics

The 16-MHz MicroADV was the main instrument used to perform flow measurements at different planes of interest relative to the DW placement. The ADV is a single-point, high-resolution instrument used to measure all 3-components of velocity in water applications. The ADV is able to measure the 3-axis velocities to 1% accuracy. It may be used for a large velocity range from 1 mm/s to 2.5 m/s and it also has excellent low-flow performance. According to the manufacturer, no calibration is necessary and the comprehensive software provided, HorizonADV, aids the process of data acquisition and processing [13]. Table 3.2 shows the basic parameters of the ADV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Rate</td>
<td>0.1 to 50 Hz</td>
</tr>
<tr>
<td>Sampling Volume</td>
<td>0.09 cm³</td>
</tr>
<tr>
<td>Distance to Sampling Volume</td>
<td>5 cm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.01 cm/s</td>
</tr>
<tr>
<td>Programmed Velocity Range</td>
<td>3, 10, 30, 100, 250 cm/s</td>
</tr>
<tr>
<td>Accuracy</td>
<td>1% of measured velocity</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>60 m</td>
</tr>
</tbody>
</table>

Figure 3.4 shows an ADV probe with specifics on how the signal is transmitted and received. Contrary to the figure obtained from the Sontek website, the sampling region for
this ADV probe is located 5 cm below the probe. According to the ADV Field Principles manual [14], the ADV measures the velocity of water using the Doppler effect. If a source is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency using Eq. 3.1 [14].

$$F_{doppler} = -F_{source}(V/C)$$  \hspace{1cm} (3.1)

In this equation, $F_{doppler}$ is the doppler shift or change in the received frequency, $F_{source}$ is the frequency of the transmitted sound, $V$ is the velocity of the source relative to the receiver, and $C$ is the speed of sound. Glass particles on the micron scale (10-20 $\mu$m) are used as seeding in the flow to increase the effectiveness of the Doppler effect [14,15].

As seen in Fig. 3.4, there is a distance from the transmitter to the sampling region. This region has a total height of 9 mm and is located 5 cm from the probe. The ADV
records nine values with each sample: three velocity values (one for each component),
three signal strength values (one for each receiver), and three correlation values (one for
each receiver) [14,15]. The signal strength and correlation are used to monitor the data
quality and to edit potentially corrupted data. In order to obtain good velocity values, the
ADV Field Manual suggests keeping the sound to noise ratio greater than 15 dB and the
correlation score greater than 70% [14,15].

For the experimental raceway flow measurements, Voleti showed that a 50 Hz sampling
rate and 6000 samples would give sufficient data to statistically converge to the true velocity
values [11].

3.2.3 ADV and PIV Preliminary Experiments

As a preliminary experiment, two DWs side-by-side were placed in the middle of the
raceway channel downstream of a flow straightener. The PW was set to run at 20 Hz,
the angle of attack was set to 40°, the water depth was 6 in., and locations 1.5 and 2.5 ft
downstream of the DWs were observed. With the help of Lance, PIV data were obtained
to observe the mixing quality created by the two DWs side-by-side.

The purpose of this experiment was to ensure mixing was present at this smaller scale
of DW. Later, ADV was used to obtain data with the same raceway parameters to be
compared to the PIV VMI results. The results of these preliminary experiment are included
in Appendix B.

3.2.4 Downstream and Side Spacing

The purpose of the downstream experiments is to measure the VMI at various locations
with respect to the DW position. Understanding that VMI for a raceway is approximately
2% without the use of DWs [11], a single location in front of the side-by-side DWs will be
observed with and without the DWs in the flow. Then 3 locations downstream of the DWs
will be observed with the DWs in the flow. This will be done for 4 PW speeds 8, 10, 12,
and 14 rpm. The VMI results will then be plotted to show the quality of mixing for the
given speeds at each location. Figure 3.5 shows the raceway with the locations of interest relative to the DW placement.

![Figure 3.5: Test matrix diagram for downstream DW side-by-side experiments: 1) PW 2) DWs 3) flow straightener](image)

Using the ADV, a grid system was setup to capture the motion of the flow. With two DWs being used, it was expected to observe 4 vortices downstream. For data acquisition of these vortices, a relatively fine grid system was setup as shown in Fig. 3.6. This grid is 5x18 with 90 total sampling stations. The traverse system used to sweep through these grid points was measured in centimeters; hence, the spacing of the grid shown reflects these units.

![Figure 3.6: 5 x 18 grid setup for ADV data acquisition](image)

Also, similar to Laws et al., the side-by-side DWs were spaced one width of a DW apart [8]. The schematic of this setup is shown in Fig. 3.7. As an array of DWs is used in a wide channel raceway, the DWs will be spaced a certain distance apart in rows such as these.

The purpose of the side spacing experiments is to quantify the mixing quality as the lateral spacing of the DWs is varied. Fig. 3.8 shows the raceway with the locations of
Fig. 3.7: Schematic of DW setup for downstream experiments

interest for the experiments. The VMI will be quantified at 3 downstream locations to ensure that the best lateral spacing is determined. The ultimate goal is to find an optimal lateral spacing for quality mixing.

Fig. 3.8: Test matrix diagram for side spacing DW side-by-side experiments: 1) PW 2) DWs 3) flow straightener

Also using the ADV, a grid system was setup to capture the vortex interaction as the lateral spacing is varied. In order to observe more of the channel, the grid was revamped to a 5x19 system. This 95 point system reaches the width limits the ADV is able to operate under without inducing interference to the instrument by contacting the channel side walls. Figure 3.9 shows the setup of the grid system used in these experiments.

Fig. 3.9: 5 x 19 grid setup for ADV data acquisition
As shown in Fig. 3.10, in 1 in. increments the $\Delta y$ will be varied from 0.5 in. to 8.5 in. The width of the DW is 4.5 in., so the varied increments will include the DW spacing between the DWs side-by-side. Literature suggests that spacing between the DW should be the length of the DW side, or airfoil [8].

![Fig. 3.10: Schematic of DW setup for side spacing experiments](image)

The combination of mixing quality and spacing are important parameters of these studies. In understanding the mixing patterns of the side-by-side DW vortices and maximizing the mixing quality by optimizing the lateral spacing, an understanding of how to set up arrays of DWs for larger scale algae growth experiments will be realized.

### 3.2.5 VMI

As determined through efforts of Voleti, the VMI is an index that is used to quantify the vertical mixing behavior in the raceway [11]. VMI helps to understand the difference in mixing quality when comparing flow measurements with and without the DWs. Due to the vortices created by the DWs, the vertical velocity components tend to cancel each other out when summed together. Thus this normalized parameter was formed, as shown in Eq. 3.2. Equations 3.3 and 3.4 represent the average of the absolute values of the vertical component
of velocity and the average streamwise velocity, respectively.

\[ VMI = \frac{W}{U} \]  
(3.2)

\[ W = \frac{\sum_{i=1}^{n} |w_i|}{n} \]  
(3.3)

\[ U = \frac{\sum_{i=1}^{n} u_i}{n} \]  
(3.4)

The components of these equations are described as follows, \( n \) is the number of grid points, \( i \) is a single grid point, \( |w| \) is the absolute value of the vertical velocity component at each grid point, \( W \) is the average of the absolute value of the vertical velocities, and \( U \) is the average streamwise velocity at the plane of interest. When multiplied by 100, VMI may be represented as a percentage. A VMI of 0% would represent zero mixing within the flow. Anything above this would show that some form of mixing is present.

### 3.2.6 VMI Uncertainty Analysis

It is important to understand the uncertainty of the obtained results. Beckwith et al. states that when estimating uncertainty, bias and precision error are the two types of error to focus on. Such errors may be obtained for single sample or multiple sample experiments [16]. The measurements of the side-by-side DW experiments are represented by multiple samples and were averaged in the process of obtaining the bias and precision errors.

Since VMI is the main parameter of interest found by the ADV measurements, it is important to look at the bias and precision errors associated with the VMI calculations. Voleti reports a \( \pm 0.3\% \) error in VMI with little explanation [11], but a closer look will be taken at how the uncertainty is calculated. After obtaining the bias and precision uncertainties, they are then combined to obtain the total uncertainty in the result [16]. The main equation of interest to solve for the uncertainty in VMI is shown in Eq. 3.5.
In this equation, $u_{VMI}$ represents the total uncertainty in VMI, $B$ stands for the bias error, and $P$ stands for the precision error. Since all terms are divided by VMI, his setup allows one to easily obtain the uncertainty in terms of percentage when multiplied by 100.

Breaking the uncertainty down, the bias error is obtained using information from the ADV settings and instrumentation. There is a $\pm 1\%$ error in the velocity measurements based on using a 100 cm/s setting in the ADV software. Also, the manual reports a resolution of 0.01 cm/s in the velocity measurement. Half the resolution is used in the uncertainty calculations. Equation 3.6 shows the expanded equation to obtain the bias error for VMI.

$$B_{VMI} = \left[ u_{v}^{2} + \left( \frac{R}{U} \right)^{2} + \left( \frac{R}{W} \right)^{2} \right]^{1/2}$$

In Eq. 3.6, $u_{v}$ represents the bias uncertainty in the velocity measurement and $R$ represents half the resolution due to the instrument itself. To get in terms of percentage, the resolution is divided by $U$ and $W$ to obtain the bias error of the velocity resolution with respect to the average streamwise and vertical velocities, respectively.

The precision error is determined from the processed data. The data gives values for the 95% span of the confidence interval for the $x$, $y$, and $z$ velocity components. Since VMI uses the $x$ and $z$ components, the precision uncertainty averaged over the entire plane of interest is found as shown in Eq. 3.7.

$$P_{VMI} = \left[ \left( \frac{\sum_{i=1}^{n} u_{ui}}{n} \right)^{2} + \left( \frac{\sum_{i=1}^{n} u_{w_i}}{n} \right)^{2} \right]^{1/2}$$

In Eq. 3.7, $n$ stands for the number of grid points, $i$ is a single grid point, $u_{ui}$ is the sum of the uncertainties in the streamwise velocity components, and $u_{w_i}$ is the sum of the uncertainties in the absolute value of the vertical velocities. The uncertainties in the streamwise and vertical velocities are summed and then averaged over the entire plane to
obtain an average precision error for the plane of interest. After the bias and precision error terms were obtained, they were combined to calculate the total uncertainty in the VMI.

3.3 Cycle Time

Much of the literature alludes to the importance of light utilization in helping increase biomass productivity. This is evident in the literature that discusses the flashing light effect or light-dark cycles. The relationship between the light-dark cycles and the cycle time is shown in how the cycle time estimates the frequency at which the algae cells circulate from top to bottom in the raceway.

Lance did much work in coming up with the cycle time parameter. Since VMI does not relate time to the algae circulation, cycle time was a newly defined parameter. According to Lance, the algal cells have to cycle from the bottom to the top (or within 1-2 in. to absorb photons from the incident radiation), and back down again to complete their cycle [12]. Equation 3.8 shows the expression of cycle time required to quantify the algae circulation.

\[
\Delta t = \frac{2D}{\sum_{i=1}^{n} |w_i|/n}
\] (3.8)

In this equation, \(D\) is the water depth, \(\sum_{i=1}^{n} |w_i|/n\) is the average vertical velocity, and \(\Delta t\) is the cycle time. This was used to observe the cycle time created by the side-by-side DW experiments.

3.4 Power Consumption Experiments

The purpose of these experiments is to observe the power required by the two DWs side-by-side. Due to the limited equipment to measure power in an accurate manner, extensive power experiments were not performed. The power was quantified for each DW side-by-side experiment. Utilizing the VFD that powers the motor to the PW, data were collected for various PW speeds.

The motor was allowed 2 hours of warm up time before hour data samples were taken and analyzed. The VFD has the specification to read power measurement within \(\pm 10W\).
This process was repeated to obtain power data for the raceway without the DWs in the flow. Software called CTScope, which acts as a virtual oscilloscope, was used in the process of collecting power data. The data were later processed with average values and standard deviations obtained through Excel spreadsheets. This setup is similar to Voleti [11].

3.5 Dimensional Analysis

Due to the fact that the DWs for these side-by-side experiments are smaller compared to the DW of Voleti and Lance’s study [11, 12], it is important to undergo a dimensional analysis to compare results of the smaller scale to the larger scale. Cengel calls this situation an incomplete similarity when the geometric similarity is not exactly possible [17].

A simple dimensional analysis shows that in order to replicate the larger scale of Lance’s 7.19 RPM data [12], the raceway flow speed needed to be approximately 40 cm/s. This requires a PW speed of about 22 RPM. This operating speed is difficult to achieve due to structural instability of the experimental raceway.

Cengel suggests that when a speed is not attainable for dimensional similarity, there are certain ways to change experimental parameters to obtain good and scalable results. This change could involve using a different fluid, changing the experimental raceway dimensions to better scale the geometries, or taking data at multiple speeds and then extrapolate the results to the full-scale Reynolds number [17]. Seeing as using a different fluid may be expensive and hard to obtain, and that changing the experimental geometry is not practical, data were taken at multiple speeds in order to extrapolate results.

In order to work around the structural stability issue, the data collected during the downstream experiments may be used to extrapolate and estimate VMI results at the larger scale. In an attempt to observe dimensionless parameters at the small and large scale and compare the VMI, the following expressions were obtained with a final result of the VMI for the large scale. The parameters denoted by a 1 represent the large scale and those denoted by a 2 represent the small scale. Reynolds numbers are equated with the VMI expression substituted for the velocity term, as shown by Eq. 3.9 and 3.10. The expression for estimating $VMI_1$ based on $VMI_2$ parameters is shown in Eq. 3.11.
\[ Re_1 = \frac{\rho V_1 D_1}{\mu} \quad (3.9) \]

\[ V_1 = \overline{U}_1 = \frac{|W_1|}{VMI_1} \quad (3.10) \]

\[ VMI_1 = VMI_2 \frac{|W_1| D_1}{|W_2| D_2} \quad (3.11) \]

In Eq. 3.11, \( D_1 \) and \( D_2 \) are the hydraulic diameter of the raceway channel, which is the flow area divided by the flow perimeter. Also, experimental data was used for the \( W_1 \) term.

Being open channel flow, it is also important to compare results using the Froude number. Equation 3.12 is the definition of Froude number with \( V \) for average velocity, \( g \) for the gravitational constant, and \( L_c \) for the channel depth. Through a similar process as shown with the Reynolds number, the expression to estimate \( VMI_1 \) was obtained as shown in Eq. 3.13.

\[ Fr = \frac{V}{\sqrt{gL_c}} \quad (3.12) \]

\[ VMI_1 = VMI_2 \frac{|W_1| \sqrt{L_2}}{|W_2| \sqrt{L_1}} \quad (3.13) \]

Using both Reynolds and Froude numbers through the dimensional analysis will help bring validity to estimating quality mixing from the small scale, 2, to the larger scale, 1. Note that these expressions for estimating \( VMI_1 \) are rough estimates based on the extrapolation of data from the experiments. More details on the assumptions and calculations are found in Appendix D.
Chapter 4

Results

This chapter outlines the results from the conducted experiments.

4.1 Algae Growth Experiments

Three growth experiments were performed. The first two experiments had the DWs installed in the south raceway and the third experiment was performed with the DWs switched to the north raceway. This was done to ensure bias was not present between the two raceways used. Through these successful experiments, it was shown that the DWs help to increase the growth of the algae. Pictures were taken after the completion of the experiments and Fig. 4.1 and 4.2 show the raceway with DWs and without DWs. This is for visual purposes to observe that the raceway with DWs is more dense than the raceway without DWs; hence, the darker green color.

Fig. 4.1: (left) Raceway with DWs, (right) Raceway without DWs
Dry weight measurements were taken for these experiments and the respective graphs may be seen in Fig. 4.3 - 4.5. Appendix A contains a statistical t-test for the mean of the three experiments and a normalized graph of the data collected to show the relative dry weight of the raceway with DWs to the peak dry weight obtained for the raceway without DWs.

![Fig. 4.2: (left) Raceway with DWs, (right) Raceway without DWs](image)

![Fig. 4.3: Dry weight data of DW vs. no DW algae growth for experiment 1. Values reported within 0.8% measurement uncertainty](image)
Fig. 4.4: Dry weight data of DW vs. no DW algae growth for experiment 2. Values reported within 0.8% measurement uncertainty.

Fig. 4.5: Dry weight data of DW vs. no DW algae growth for experiment 3. Values reported within 0.8% measurement uncertainty.
Table 4.1 also shows the peak-to-peak growth values and the percent increase in biomass production due to the addition of the DWs. The results show that the DWs help increase the biomass production by 25.4%, 29.6%, and 25.4% for experiments 1, 2, and 3, respectively.

Table 4.1: Peak-to-peak data comparison of algae growth experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>DW</th>
<th>No DW</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.281</td>
<td>0.224</td>
<td>25.4%</td>
</tr>
<tr>
<td>2</td>
<td>0.21</td>
<td>0.162</td>
<td>29.6%</td>
</tr>
<tr>
<td>3</td>
<td>0.217</td>
<td>0.173</td>
<td>25.4%</td>
</tr>
</tbody>
</table>

These results are encouraging. They confirm that the previous DW flow studies were not wasted and that the DW does indeed help increase the biomass production. It is also important to remember that the DW and channel dimensions were not optimal. Hence, in the case of such an increase in growth against the non-ideal dimensional parameters, it may be possible to see an even larger increase in biomass productivity as the dimensions are optimized. Further flow measurement and growth experiments would have to be completed to confirm this assumption.

These conclusions lead to the question of what is next to be done? As raceways become larger, the channel widens and a single DW cannot suffice. Similar to Laws et al. [8], an array of DWs will have to be used to induce mixing within the long straight sections of the raceway channel. The next section presents the results of the side-by-side DW experiments to show quality mixing is still obtained as an array of DWs are used.

4.2 SANT Raceway Experiments

4.2.1 Downstream

After the successful growth experiments, DW side-by-side experiments were conducted to quantify mixing as DWs are put in arrays in the channel. VMI was calculated for 4 PW speeds and at 4 locations relative to the DW position. One location upstream with and without the DWs, and 3 locations downstream were observed with the DWs in the flow.
The velocity data were collected using the ADV. A view of the data acquisition setup of the ADV relative to the side-by-side DW location is shown in Fig. 4.26.

After data processing, the $y$ and $z$ velocity components were inserted into Matlab to obtain velocity-vector plots. This helped to visualize the flow patterns in the channel. The flow downstream is anticipated to have 4 vortices due to the side-by-side DWs. This is observed for all 4 flow speeds; however, the vortices near the channel walls are cut off due to the limitations of the ADV not being able to collect flow measurements up to the channel walls. This may result in lower VMI values. The preliminary ADV and PIV data helps show that the VMI results will be lower due to the smaller region that the ADV captures relative to PIV measurements that captured the entire plane of interest. This may be seen in the details of Appendix B.

Figures 4.6 - 4.25 show the flow patterns in the open channel raceway for PW speeds of 8, 10, 12, and 14 RPM, respectively. First, the upstream location without and with the DW in the flow are shown, followed by the 3 downstream locations for each PW speed.

![Figure 4.6: In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 8 RPM](image-url)
Fig. 4.7: In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 8 RPM

Fig. 4.8: In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 8 RPM
Fig. 4.9: In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 8 RPM

Fig. 4.10: In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 8 RPM
Fig. 4.11: In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 10 RPM

Fig. 4.12: In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 10 RPM
Fig. 4.13: In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 10 RPM

Fig. 4.14: In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 10 RPM
Fig. 4.15: In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 10 RPM

Fig. 4.16: In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 12 RPM
Fig. 4.17: In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 12 RPM

Fig. 4.18: In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 12 RPM
Fig. 4.19: In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 12 RPM

Fig. 4.20: In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 12 RPM
Fig. 4.21: In-plane velocity vector field obtained at 1 ft upstream of the DW original location (no DW in channel) for a PW speed of 14 RPM

Fig. 4.22: In-plane velocity vector field obtained at 1 ft upstream of the DW for a PW speed of 14 RPM
Fig. 4.23: In-plane velocity vector field obtained at 1 ft downstream of the DW for a PW speed of 14 RPM

Fig. 4.24: In-plane velocity vector field obtained at 2 ft downstream of the DW for a PW speed of 14 RPM
Fig. 4.25: In-plane velocity vector field obtained at 3 ft downstream of the DW for a PW speed of 14 RPM

As expected, for each PW speed there are 4 vortices present downstream of the DWs. Each speed appears to have good circulation of the vortices as they propagate downstream. By the 3 ft location, however, certain speeds such as 8 RPM, the vortices appear to be interacting to the point that the circulation is being destroyed. The vortices near the channel wall for all cases appear to be dissipating as well. This might be expected due to the viscous effects near the wall.

It was also observed that near the channel floor between the two middle vortices, a deadzone or stagnation region was created. This may be seen in Fig. 4.26 where the minerals, salt, and hard water deposits form a line along the channel in this stagnation region. This may be a concern when growing algae, seeing as some cells may get captured and stick to the channel floor. Staggering the DW arrays relative to one another may be necessary in efforts to remix the material caught in the stagnation zones. How this affects biomass productivity may not be determined unless growth experiments are performed.

Along with these observations, VMI was calculated at each location for each PW speed. The uncertainty analysis was performed on the VMI results and respective error bars with the VMI results are presented in Fig. 4.27. The VMI results represented are of those calculated from data of the side-by-side DWs in the flow. As data were collected further
downstream, the exponential decay in VMI would result. The trend may return to normal raceway mixing conditions of about 2% around 6-8 ft downstream.

For comparison purposes, the VMI results of the one upstream location of the DW in and out of the flow are tabulated as follows in Table 4.2. The percent difference in the values indicate that the DWs induce perturbations that extend upstream. However, the 2% represented by the data without the DWs in the flow support the findings that the raceway without DWs results in a VMI of 2% [11].

Table 4.2: VMI comparison of DW or no DW at location 1 ft in front of side-by-side DWs

<table>
<thead>
<tr>
<th>PW (RPM)</th>
<th>DW VMI</th>
<th>No DW VMI</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2.58</td>
<td>2.13</td>
<td>20.5</td>
</tr>
<tr>
<td>10</td>
<td>2.51</td>
<td>1.91</td>
<td>31.3</td>
</tr>
<tr>
<td>12</td>
<td>2.45</td>
<td>1.87</td>
<td>30.8</td>
</tr>
<tr>
<td>14</td>
<td>2.53</td>
<td>2.05</td>
<td>23.6</td>
</tr>
</tbody>
</table>

For the downstream experiments, VMI was quantified for 4 PW speeds at 4 locations. The side-by-side DWs induce mixing that propagates good distances downstream. The vortices do not interact to the point of destroying one another until further downstream;
hence, desired circulation was observed. Also, the direction of vortices appears to cause stagnation regions that capture hard water and salt deposits in the flow. Understanding that good mixing is still present as more DWs are added in an array, it was important to understand the optimal lateral spacing between the DWs. This would help quantify mixing and understand the best setup for multiple arrays of DWs.

As explained in Chapter 3, the cycle time $\Delta t$ was to be obtained for the various locations and flow speeds of the downstream experiments. Figure 4.28 shows the calculated cycle times. The location of greatest VMI was expected to have the fastest cycle time.

In comparing results to those of Lance, the cycle time of these experiments appears rather slow [12]. However, there may be a geometric connection between these small scale data with the larger scale. More data would need to be collected to confirm the validity of geometric relationships, but taking the cycle time data obtained from Lance for a 10.54 RPM and dividing by the cycle time of 10 RPM of the downstream experiments, it was
found that the ratio is approximately 3.07. This means that the cycle time of Lance’s data is about 3 times faster than these downstream experimental data [12].

4.2.2 Side Spacing

The setup of the downstream distance experiments was to be similar to Laws et al. where the width of the DW was spaced between the side-by-side DWS [8]. Next question at hand was to see if there is an optimal spacing between the DWs. The spacing suggested by Laws et al. seems to be arbitrary and no reason is presented to back it up. Cheng and Dugan suggest spacing the plates the width of the plate apart since this setup seemed to give the best mixing situation, but no extensive optimization study was performed [9].

Therefore, the side-by-side DW experiments were conducted to observe the VMI against the lateral spacing $\Delta y$ between the DWs. The spacing was increased from 0.5 in. to 8.5 in. with increments of 1 in. This was done to observe the best spacing between the side-by-side
DWs. Three downstream locations were observed for each lateral spacing. The PW was run at 12 RPM for each data acquisition series and the ADV was used to measure the velocity data. The VMI for these locations and side spacings were quantified to find an optimal lateral spacing of the DWs in the array.

After data processing, the y and z velocity components were inserted into Matlab to obtain velocity-vector plots. This helped to visualize the flow patterns in the channel and observe the vortex interactions as they propagated downstream.

Figures 4.29 - 4.55 show the effects of vertical mixing as the lateral spacing of the side-by-side DWs was changed from 0.5 in. spacing to 8.5 in. spacing in 1 in. increments.

![In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 0.5 in. laterally](image)
Fig. 4.30: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 0.5 in. laterally

Fig. 4.31: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 0.5 in. laterally
Fig. 4.32: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 1.5 in. laterally

Fig. 4.33: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 1.5 in. laterally
Fig. 4.34: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 1.5 in. laterally

Fig. 4.35: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 2.5 in. laterally
Fig. 4.36: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 2.5 in. laterally

Fig. 4.37: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 2.5 in. laterally
Fig. 4.38: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 3.5 in. laterally

Fig. 4.39: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 3.5 in. laterally
Fig. 4.40: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 3.5 in. laterally

Fig. 4.41: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 4.5 in. laterally
Fig. 4.42: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 4.5 in. laterally

Fig. 4.43: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 4.5 in. laterally
Fig. 4.44: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 5.5 in. laterally

Fig. 4.45: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 5.5 in. laterally
Fig. 4.46: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 5.5 in. laterally.

Fig. 4.47: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 6.5 in. laterally.
Fig. 4.48: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 6.5 in. laterally

Fig. 4.49: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 6.5 in. laterally
Fig. 4.50: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 7.5 in. laterally

Fig. 4.51: In-plane velocity vector field obtained at 2 ft downstream of the DW spaced 7.5 in. laterally
Fig. 4.52: In-plane velocity vector field obtained at 3 ft downstream of the DW spaced 7.5 in. laterally.

Fig. 4.53: In-plane velocity vector field obtained at 1 ft downstream of the DW spaced 8.5 in. laterally.
By observation of the Matlab plots, there are a few different points of interest concerning the vortex interaction. It is apparent that the vortices in the spacing from 0.5 in. to 3.5 in. are too close to each other. This may be seen by the 3 ft location that the two middle vortices are competing with one another until they destroy each other.

The 4.5 in. spacing appears to have good vortical motion at all observed locations. This was to be expected since the setup was the same as the downstream experiments.
Also, as shown in Fig. 4.56, the 4.5 in. lateral spacing ended up being the best spacing between DWs for best mixing conditions.

Lastly, the 5.5 in. to 8.5 in. spacing showed a decline in VMI as the spacing increased. The 1 ft locations appear to have relatively straight or noncirculating flow passing between the DWs. As the vortices propagate to the 2 ft and 3 ft locations, it appears that the vortices slow down and fill the space of the channel. Although mixing appears present, the VMI results show lower results at these locations compared to the optimal 4.5 in. spacing.

Similar to the downstream experiments, each spacing tested also had a stagnation region present between the two middle vortices. By observation, this stagnation region continued further downstream for higher VMI values. As the DWs are close together, the vortices compete and destroy each other not far downstream. Hence, the circulation causing the stagnation region is disrupted and the line of minerals and hard water deposits spreads out along the channel floor. This also happens as the strength of the vortices weakens and slows down due to the uniform flow through the space available for the large DW spacing. This stagnation region appeared to continue furthest downstream for the 4.5 in. spacing.

It is still unknown whether this stagnation region or deadzone captures the algae and forces the cells to stick to the channel floor. However, it is more important to provide the best possible VMI or vortex circulation downstream to help the algal cells cycle through the light and dark regions during the growth process.

Along with these observations, VMI was calculated at each location for each lateral spacing. The uncertainty analysis was performed on the VMI results and respective error bars with the VMI results are presented in Fig. 4.56. The VMI results represented are of those calculated from data of the side-by-side DWs in the flow. The graph of VMI versus lateral spacing at each downstream location helps to show that the 4.5 in. spacing is optimal for this DW array. This is shown by the peak at the 1 ft, 2 ft, and 3 ft locations for the 4.5 in. spacing. This peak of lateral spacing was desired in the process of these experiments.

By varying the lateral spacing of the side-by-side DWs and measuring velocities at 3 downstream locations, an optimal lateral spacing between DWs to be put in an array
Fig. 4.56: Side spacing VMI results relative to downstream locations of side-by-side DWs was obtained. The 4.5 in. spacing proved to be the best spacing for quality VMI values. By observation, no matter the lateral spacing, large or small, there was a presence of a stagnation region between the two center vortices. It was seen that as VMI increases, the stagnation region extended further down the channel. It would be important to understand how this region affects algal growth. An example of the stagnation region for the side spacing experiments is shown in Fig. 4.57.

Fig. 4.57: (left) 0.5 in. lateral side spacing of DWs front view, (right) downstream view of stagnation line created by 0.5 in. side spacing of DWs
The cycle time $\Delta t$ was also obtained for the side-by-side DW experiments for each respective lateral spacing. Figure 4.58 shows the calculated cycle times for the various spacings at all 3 locations of interest. The location of greatest VMI was expected to have the fastest cycle time. Hence, the optimal DW spacing was found to have the fastest cycle time.

Unlike the downstream experiments, there are no data available to relate the cycle time of these smaller scale experiments to larger scale applications. However, it was assumed that the calculated cycles times are approximately 3 times slower than those found at the scale of Lance [12].

### 4.3 Power Consumption

Power was recorded using the VFD and CTScope software in order to observe the required input power with and without the side-by-side DWs in the flow. Naturally, the DW creates a drag force that requires more power input to the motor to compensate the force felt by the PW. Values for power are tabulated to show the percent increase in power due to the side-by-side DWs in both the downstream and side spacing experiments. The downstream power requirements were obtained for all tested PW speeds. The side spacing experiments used a single PW speed and just the DWs in the flow. The average and standard deviation over the hour data acquisition period are represented in the Table 4.3.

<table>
<thead>
<tr>
<th>PW (RPM)</th>
<th>DW (W)</th>
<th>No DW (W)</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>35.92±4.92</td>
<td>34.45±4.99</td>
<td>4.26</td>
</tr>
<tr>
<td>10</td>
<td>49.93±4.48</td>
<td>46.78±4.70</td>
<td>6.74</td>
</tr>
<tr>
<td>12</td>
<td>64.04±5.62</td>
<td>60.21±5.26</td>
<td>6.38</td>
</tr>
<tr>
<td>14</td>
<td>79.31±7.09</td>
<td>75.37±6.25</td>
<td>5.23</td>
</tr>
</tbody>
</table>

The ± values represent the standard deviation in the average power consumed. It is shown that with the increase in power, from PW speeds of 8 RPM to 14 RPM, there is an increase in power consumption due to the DW drag force. For the scale of these
Fig. 4.58: Side spacing cycle time results relative to the lateral spacing of side-by-side DWs experiments, an average power increase of approximately 1.5 W was found for a single DW. This conclusion is supported by the findings of Lance [12].

Power measurements were also taken for the side spacing experiments. However, it was observed that the change in lateral spacing did not change the required power input. Since two DWs were used, the same power consumption reported for the 12 RPM results in Table 4.3 was observed. The main method of increasing the power requirements is increasing the number of DWs in an array.

### 4.4 Dimensional Analysis Results

It is important to do a dimensional analysis using the experimental data obtained to extrapolate and estimate VMI results of the side-by-side DW experiments at a larger scale. Data from Lance’s thesis were used for this purpose [12]. As suggested by Cengel [17], Reynolds numbers were matched. Also, since this involves open channel flow, Froude numbers were matched. VMI representations for the large scale and small scale DW data
were used.

The results are shown in Table 4.4 and 4.5 with the accompanying percent difference in the approximation to the real value. Table 4.4 used the vertical velocity components relative to the location in equating Reynolds numbers and Table 4.5 used the same experimental data in equating the Froude numbers.

Table 4.4: Dimensional analysis to estimate $VMI_1$ from Eq. 3.11 (Reynolds number)

<table>
<thead>
<tr>
<th>Location (ft)</th>
<th>$VMI_1$ Estimate</th>
<th>$VMI_1$ Exact</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.432</td>
<td>0.353</td>
<td>22.6</td>
</tr>
<tr>
<td>2</td>
<td>0.344</td>
<td>0.272</td>
<td>26.8</td>
</tr>
<tr>
<td>3</td>
<td>0.307</td>
<td>0.236</td>
<td>30.5</td>
</tr>
</tbody>
</table>

Table 4.5: Dimensional analysis to estimate $VMI_1$ from Eq. 3.13 (Froude number)

<table>
<thead>
<tr>
<th>Location (ft)</th>
<th>$VMI_1$ Estimate</th>
<th>$VMI_1$ Exact</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.235</td>
<td>0.353</td>
<td>33.3</td>
</tr>
<tr>
<td>2</td>
<td>0.187</td>
<td>0.272</td>
<td>31.1</td>
</tr>
<tr>
<td>3</td>
<td>0.120</td>
<td>0.236</td>
<td>15.3</td>
</tr>
</tbody>
</table>

It is shown that through this rough dimensional analysis, the estimate was within an average 26.6% of the true VMI value for Table 4.4 and an average 26.5% of the true VMI value for Table 4.5. The Reynolds number equation appeared to overestimate the VMI values, whereas the Froude number equation underestimated the VMI values.

This rough extrapolation showed relatively good results with a fair estimate of VMI at the larger scale when equating both Reynolds and Froude numbers. This suggests that if the side-by-side DW experiments were done at a larger scale, the mixing quality would still be substantial and desired circulation patterns would still be produced. Hence, the mixing quality due to side-by-side DWs is present and one may assume that arrays of multiple DWs would also allow quality mixing. Detailed calculations for the dimensional analysis may be found in Appendix D.
Chapter 5
Conclusions and Future Recommendations

The research efforts of Voleti, Godfrey, and Lance helped set the stage for the work conducted in this thesis [10–12]. The DW was shown to be an effective mechanism in increasing the vertical mixing within the open channel raceway. Literature shows few examples of algae growth experiments using mixing mechanisms. Utilizing the DW, algae growth experiments were performed and yielded positive results. The next step in understanding mixing quality of two DWs side-by-side was performed. Experiments were designed and conducted to quantify VMI of the two DWs side-by-side for various PW speeds. The lateral spacing was varied to observe an optimal spacing between DW in an array. The results showed that quality mixing is present in the side-by-side DW experiments. The main conclusions of this research were found to be:

- Algae growth experiments were performed using a *Chlorella Vulgaris* strain. The results after three successful experiments show an average 27.1% increase in biomass productivity due to the DW addition. These results are encouraging, despite the non-optimal raceway dimensions, and show that previous research efforts were worthwhile.

- DW side-by-side experiments were performed to quantify VMI vs. downstream distance. The VMI results show mixing is present and that if continued downstream, the vortices would dissipate and return to regular raceway conditions between 6-8 ft.

- DW side-by-side experiments were also performed to obtain optimal lateral spacing of DWs in an array. The optimal spacing was found to be a DW spacing between the side-by-side DWs.
• Cycle time was calculated for each set of experiments. The ratio of cycle time of the side-by-side DW experiments compared to data collected by Lance was about 3, meaning that the cycle time of Lance’s data was 3 times faster [12].

• Power consumption experiments were performed to tabulate the input power required for the addition of each DW. The power increase due to a single DW was approximated at 1.5 W. Slower PW speeds may be used to sustain mixing and cut power costs.

• A rough dimensional analysis was performed to estimate the VMI from the small side-by-side DW scale to the larger scale used by Voleti and Lance [11, 12]. These rough estimates show approximately an average of 26.6% and 26.5% accuracy in predicting VMI at larger scales when equating Reynolds and Froude numbers, respectively. There is confidence that if run at a larger scale, quality mixing would still be present using arrays of DWs.

• As shown in Appendix B, the preliminary ADV and PIV experiments provided information that mixing was present at this small scale. PIV was able to see more of the raceway channel compared to ADV and obtained higher VMI values. However, it was seen that the vortices did not circulate to the top of the water hinting that the DW VMI may decrease with increasing water depth.

• CFD simulations were performed, as shown in Appendix C. These simulations show that a free-surface volume of fluid wave has a greater impact on the DW vortex dissipation rates compared to the simple slip-wall boundary condition. The free-surface represents a closer to reality solution and would need to be implemented for future CFD work compared to using a slip-wall condition.

Through the efforts of this study, vertical mixing patterns of two DWs side-by-side are better understood. This knowledge will help in setting up algae growth experiments using arrays of DWs. The following are suggestions for future work.

Although it was determined that quality mixing may be obtained at a larger scale, it is important to understand the placement of arrays relative to one another. This is important
because of the deadzones or stagnation regions that were observed. Ideally, the arrays may be staggered downstream to allow the algal cells and minerals caught in these zones to remix in the main flow. If these stagnation regions do not have a noticeable effect on biomass production, then the arrays will most likely aligned for simplicity and continued downstream mixing. Algae growth experiments would need to be performed to understand this better.

It would be important to understand an optimal depth for DW operation. The CFD simulations, outlined in Appendix C, suggest that water too shallow would dissipate the vortices faster, whereas the PIV and CFD data suggest that water too deep would have regions of unmixed flow since the DW vortices appear to be localized around its centroid. Even though the algae growth experiments saw an increase in productivity, scaling the geometry to have best quality mixing may increase the productivity even more.

Along with the CFD simulations, if they are to be looked at further, it would be suggested that a free-surface boundary condition be used for computational analysis. This would increase the computational capability of predicting flow patterns, dissipation and other turbulence parameters relevant to the USU research efforts.

Lastly, completing all these suggested work for the future would lead to the capability of creating a computational model that could be used to predict algae growth based on computational and experimental knowledge obtained through the various research efforts.
References


Appendices
Appendix A

Algae Growth Experiments

A.1 Experimental Growth Data

This section contains the data from the algae growth experiments represented in a statistical t-test for the mean of the three experiments. As suggested by Beckwith [16], the t-test is performed with small sample distributions. From the three experiments, the sample mean and standard deviation of dry weight were calculated for the DW and no DW data using Eq. A.1 and A.2. Using the t-tables from Beckwith [16], for confidence levels of 95, 90, and 80 %, t-values of 4.303, 2.92, and 1.886 are obtained, respectively. Hence, the sample mean, t-value, and standard deviation are plugged into Eq. A.3 to obtain the confidence intervals.

\[
\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = \frac{x_1 + x_2 + x_3}{3} \\
S_x = \sqrt{\frac{(x_1 - \bar{x})^2 + (x_2 - \bar{x})^2 + (x_3 - \bar{x})^2}{n}}
\]

\[
\bar{x} - t_{\alpha/2,\nu} \frac{S_x}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2,\nu} \frac{S_x}{\sqrt{n}}
\]

Figures A.1 - A.3 show the 95, 90, and 80% confidence levels of the measured values for all three experiments, respectively. The confidence levels means that it is confident that the true value lies in the span of the error bars. Although the experiments were controlled, the graphs show a relatively large span for the confidence level may be due to a few reasons. The main reason being certain variables that could not be well regulated. These include a combination of sunlight and the sodium growth lamps used varied depending on the day.
The growth lamps were consistent, but the sunlight varied. Also, at the beginning of each experiment, the initial inoculum levels varied. These varying levels resulted in slightly different max growth values. Also, temperatures in the greenhouse varied by day, despite the cooling coils used in the raceways. These varying parameters may have resulted in the large error bars, but the relative growth comparisons, shown in the normalized study, help to understand that the percent increase due to the DWs was consistent overall.

![95% Confidence Interval](image)

Fig. A.1: 95% confidence interval from t-test on mean of algae growth experiments
Fig. A.2: 90% confidence interval from t-test on mean of algae growth experiments

Fig. A.3: 80% confidence interval from t-test on mean of algae growth experiments
The data collected were also normalized as follows. The y-axis represents dry weight of the raceway with DWs normalized by the peak growth value of the raceway without DWs, where unity is equal to 1. Any value above the normalized value of 1 represents an increase in growth due in the raceway with DWs relative to the raceway without DWs. The normalized variable for dry weight is defined in Eq. A.4.

\[
DryWeight_{\text{norm}} = \frac{\text{Dry Weight with DWs}}{\text{Peak Dry Weight without DWs}} \tag{A.4}
\]

Also, the tabulated peak-to-peak growth values for all three algae growth experiments are shown. These data were used to obtain the average increase in growth over the three experiments, which was found to be 27.1%.

Table A.1: Peak-to-peak data comparison of algae growth experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>DW</th>
<th>No DW</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.281</td>
<td>0.224</td>
<td>25.4</td>
</tr>
<tr>
<td>2</td>
<td>0.210</td>
<td>0.162</td>
<td>29.6</td>
</tr>
<tr>
<td>3</td>
<td>0.217</td>
<td>0.173</td>
<td>25.4</td>
</tr>
</tbody>
</table>
Fig. A.4: Normalized dry weight values for DW relative to peak dry weight values for no DW
Appendix B

ADV and PIV Preliminary Experiments

B.1 Experimental Data

Table B.1 and B.2 represent the VMI and cycle time for PIV and ADV during the preliminary experiment, respectively. The values for PIV are larger than ADV due to the fact that the PIV is able to observe the entire channel, whereas the ADV only views a portion of it. This is eminent in the Matlab plots in the following sections.

Table B.1: VMI comparison using PIV and ADV

<table>
<thead>
<tr>
<th>Location Downstream (ft)</th>
<th>PIV</th>
<th>ADV</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>0.167</td>
<td>0.071</td>
<td>57.7</td>
</tr>
<tr>
<td>2.5</td>
<td>0.159</td>
<td>0.049</td>
<td>69.4</td>
</tr>
</tbody>
</table>

Table B.2: Cycle time comparison using PIV and ADV

<table>
<thead>
<tr>
<th>Location Downstream (ft)</th>
<th>PIV (s)</th>
<th>ADV (s)</th>
<th>% Diff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>23.14</td>
<td>26.20</td>
<td>13.2</td>
</tr>
<tr>
<td>2.5</td>
<td>24.55</td>
<td>38.31</td>
<td>56.1</td>
</tr>
</tbody>
</table>
Fig. B.1: In-plane velocity vector field obtained at 1.5 ft downstream of the DW for a PW speed of 20 Hz using PIV

Fig. B.2: In-plane velocity vector field obtained at 2.5 ft downstream of the DW for a PW speed of 20 Hz using PIV
ADV Experimental Data

Fig. B.3: In-plane velocity vector field obtained at 1.5 ft downstream of the DW for a PW speed of 20 Hz using ADV

Fig. B.4: In-plane velocity vector field obtained at 2.5 ft downstream of the DW for a PW speed of 20 Hz using ADV
Appendix C

CFD Vortex Dissipation Study

C.1 Simulation Description

CFD was used to observe the vortex dissipation rates of a DW with respect to increasing water depth. Depths of 9.5, 10, 11, 12, 13, 14, and 15 in. were used for the simulations. Two approximation methods, a slip-wall top surface and a free-surface boundary condition, were used and yielded different results. Both the slip-wall and free-surface approximations show that dissipation rates decrease as water depth increases. However, the dissipation rate of the free surface approximation shows a larger change in dissipation rates. Hence, it was concluded that the free surface has a larger effect on the overall vortex dissipation than the slip-wall condition. The results suggest that the free surface condition represents a more real case scenario. Hence, these results suggest that the free surface makes the DW vortices dissipate at higher rates as the water depth decreases. The following graphs show the results of the velocity magnitude and dissipation rates for the various water depths, respectively.

Fig. C.1: CFD DW simulation showing streamlines of fluid motion
C.2 Slip-Wall Approximation

For the slip-wall condition, the inlet was set to a velocity inlet with a split-flow outlet on the end of the channel. The inlet velocity was set to 0.3 m/s. The following results show the magnitude of the velocity in the channel and the dissipation rate vs. increase in water depth, respectively.

![Slip-Wall Vmag](image)

**Fig. C.2:** Magnitude of velocity in channel with respect to increasing water depth for a slip-wall boundary condition

Also, it was desired to view the vortex shape as the water depth increased. The following figures show that with increasing water depth, the vortex appears more circular. This shows that the shallow water squeezes the vortices, resulting in a higher dissipation rate. As the depth increases, the dissipation rate decreases and the vortices show a more circular pattern.
Fig. C.3: Dissipation rate of DW vortices with respect to increasing water depth for a slip-wall boundary condition

Fig. C.4: CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 9.5 in. water depth
Fig. C.5: CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 10 in. water depth

Fig. C.6: CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 11 in. water depth
Fig. C.7: CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 12 in. water depth

Fig. C.8: CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 13 in. water depth
Fig. C.9: CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 14 in. water depth

Fig. C.10: CFD scalar velocities for a slip-wall condition 1 ft downstream of DW position at 15 in. water depth
C.3 Free-Surface Approximation

For the free-surface condition, the inlet was set to a velocity inlet with a split-flow outlet on the end of the channel. The inlet and volume of fluid wave velocities were set to 0.3 m/s. The following results show the magnitude of the velocity in the channel and the dissipation rate vs. increase in water depth, respectively. Compared to the slip-wall simulations, it appears that the free-surface has a greater effect on the dissipation of the vortices.

![Free-Surface Vmag](image)

Fig. C.11: Magnitude of velocity in channel with respect to increasing water depth for a free-surface boundary condition

Also, it was desired to view the vortex shape as the water depth increased. The following figures show that with increasing water depth, the vortex appears more circular. This shows that the shallow water squeezes the vortices, resulting in a higher dissipation rate. As the depth increases the dissipation rate decreases and the vortices show a more circular pattern.
Fig. C.12: Dissipation rate of DW vortices with respect to increasing water depth for a free-surface boundary condition

Fig. C.13: CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 9.5 in. water depth
Fig. C.14: CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 10 in. water depth

Fig. C.15: CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 11 in. water depth
Fig. C.16: CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 12 in. water depth

Fig. C.17: CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 13 in. water depth
Fig. C.18: CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 14 in. water depth

Fig. C.19: CFD scalar velocities for a free-surface condition 1 ft downstream of DW position at 15 in. water depth
Appendix D

Dimensional Analysis

D.1 Dimensional Analysis

The following is the dimensional analysis used to estimate the values obtained in Chapter 4. As suggested by Cengel [17], data were obtained at multiple speeds for the side-by-side DW experiments. These data were then used to extrapolate values necessary to estimate $VMI_1$ as described in section 3.5. First, it is important to note the data used for these calculations. Table D.1 and D.2 represent the side-by-side DW data and Blake’s 7.19 RPM data, respectively. Also note that the data for Blake’s study was found at 3 slightly different distances downstream of the DW. This may add to the error of estimation. If time allowed, more careful measurements could be completed to do a more thorough dimensional analysis.

Table D.1: Side-by-side DW vertical velocity components

<table>
<thead>
<tr>
<th>Location (ft)</th>
<th>8 RPM</th>
<th>10 RPM</th>
<th>12 RPM</th>
<th>14 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.037</td>
<td>1.418</td>
<td>1.358</td>
<td>1.633</td>
</tr>
<tr>
<td>2</td>
<td>0.669</td>
<td>1.106</td>
<td>1.104</td>
<td>1.335</td>
</tr>
<tr>
<td>3</td>
<td>0.569</td>
<td>0.895</td>
<td>0.845</td>
<td>1.131</td>
</tr>
</tbody>
</table>

Table D.2: 7.19 RPM vertical velocity and VMI data from [12]

<table>
<thead>
<tr>
<th>Location (ft)</th>
<th>Vertical Velocity</th>
<th>VMI_1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.17</td>
<td>4.689</td>
<td>0.353</td>
</tr>
<tr>
<td>2.17</td>
<td>3.612</td>
<td>0.272</td>
</tr>
<tr>
<td>3.17</td>
<td>3.133</td>
<td>0.236</td>
</tr>
</tbody>
</table>

The difference in vertical velocity components of Table D.1 were averaged to obtain a basic linear increase in increments of 2 RPM. This simple linear interpolation was used
to obtain an estimated vertical velocity component for 22 RPM. Also, since VMI is not a strong function of average flow velocity [12], the $VMI_2$ data were averaged and used in the calculation. Table D.3 shows the 22 RPM VMI and vertical velocity component values for the 3 locations of interest.

Table D.3: Interpolated vertical velocity 2 and $VMI_2$ data for 22 RPM

<table>
<thead>
<tr>
<th>Location (ft)</th>
<th>Vertical Velocity 2</th>
<th>$VMI_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.587</td>
<td>0.167</td>
</tr>
<tr>
<td>2</td>
<td>2.230</td>
<td>0.149</td>
</tr>
<tr>
<td>3</td>
<td>2.014</td>
<td>0.139</td>
</tr>
</tbody>
</table>

Using these data and the equations for dimensional analysis, outlined in section 3.5, the VMI for a larger scale was estimated in two ways. First, as shown in Fig. D.1, the original data was used to estimate $VMI_1$ by equating Reynolds numbers.

![Fig. D.1: Excel work of the dimensional analysis equating Reynolds numbers](image-url)
Figure D.2 shows the results from equating Froude numbers. This is done by using the experimental data in Eq. 3.13 to estimate VMI₁.

<table>
<thead>
<tr>
<th>location</th>
<th>w₁</th>
<th>vmi₁</th>
<th>location</th>
<th>w₂</th>
<th>vmi₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.17 ft</td>
<td>4.69</td>
<td>0.353</td>
<td>1 ft</td>
<td>2.59</td>
<td>0.167</td>
</tr>
<tr>
<td>2.17 ft</td>
<td>3.61</td>
<td>0.272</td>
<td>2 ft</td>
<td>2.23</td>
<td>0.149</td>
</tr>
<tr>
<td>3.17 ft</td>
<td>3.13</td>
<td>0.236</td>
<td>3 ft</td>
<td>2.01</td>
<td>0.139</td>
</tr>
</tbody>
</table>

**Fig. D.2: Excel work of the dimensional analysis equating Froude numbers**