SBI Science & Technology Review Winter Meeting Jan. 29th 2013

EXPERIMENTAL INVESTIGATIONS OF VERTICAL MIXING IN AN ALGAL RACEWAY USING DELTA WINGS

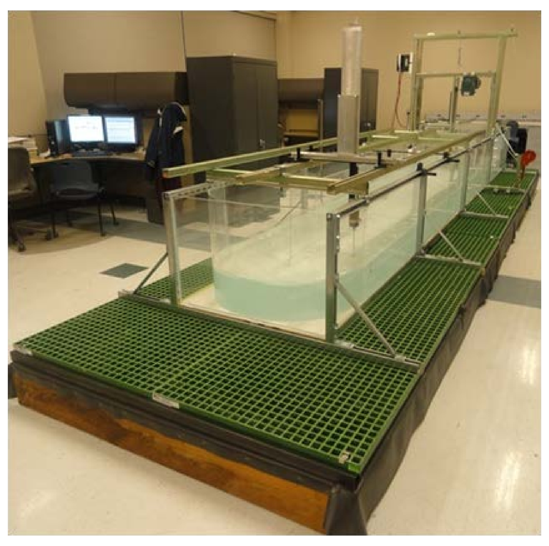
RAM VOLETI, GARRETT VAUGHAN, JAYSON PEMBERTON, BYARD WOOD
DEPARTMENT OF MECHANICAL & AEROSPACE ENGINEERING, UTAH STATE UNIVERSITY, LOGAN, UT

UtahStateUniversity SYNTHETIC BIOMANUFACTURING INSTITUTE

USTAR Turning innovation into industry.

BioEnergy Center

ABSTRACT

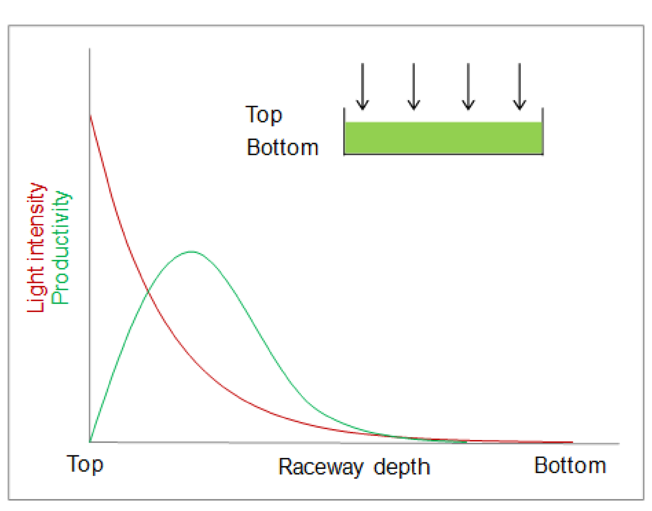

Lab-scale raceway setup

Turbulent mixing plays an important role in the distribution of sunlight, CO_2, and nutrients for algae in the raceway ponds. Mixing prevents settling of the algal biomass and keeps the nutrients and incident sunlight in active contact with the algae cell surface. In the literature survey, studies with increased productivities have been demonstrated in algal cultures when mixing was improved. For large-scale outdoor raceways the choice of mixing technology still needs to be evaluated. The objective of this research was to study raceway hydrodynamics with an emphasis on increasing algal vertical mixing. Delta wings were used to study mixing characteristics in the raceway. Experimental studies were performed to quantify the vertical mixing with and without delta wings in a raceway at approximately the same power consumption. Velocity vector profiles and mixing parameters were measured using an Acoustic Doppler Velocimeter (ADV) at various locations along the entire length of the raceway. Vortices were observed in the raceway up to a distance of around 3 m downstream of the delta wing. The results indicated that the addition of delta wings increase the vertical mixing intensity or circulation of algae cells over the raceway depth. This sort of systematic vertical mixing plays an important role to produce the flashing light effect on algal mass culture.


Delta wing in the raceway

INTRODUCTION

Raceway ponds have been the most common choice for outdoor algal production because they cost less to build and operate although they have low algal biomass productivity compared to engineered photobioreactors. One of the challenges in a raceway pond is to maintain adequate mixing and circulation velocity with minimal energy input. One of the major purposes for algal pond mixing is to move algae in and out of the light zone, thus improving distribution of sunlight to the cells, for optimal photosynthesis. Hence, vertical mixing is of primary interest. Usually raceway ponds are not deeper than 15–30 cm because of the need to keep the algae exposed to sunlight and the limited depth to which sunlight can penetrate the pond water (see Figures 1 and 2). Optimal pond mixing has been shown to be between 15 and 30 cm/s of channel velocity.



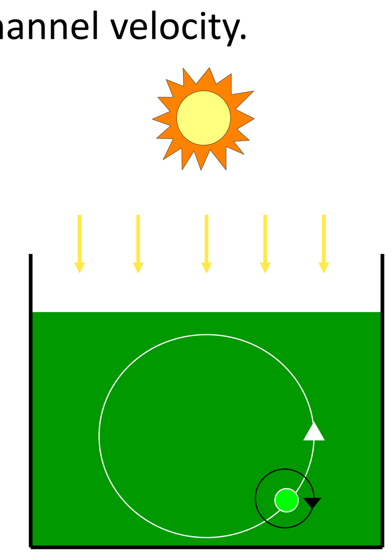


Figure 1. Theoretical representation of algae productivity against light intensity
Figure 2. General representation of algal raceway pond hydrodynamics

MATERIALS & METHODS

A scaled model clear acrylic raceway was designed and constructed for the flow visualization studies. The test flume cross-section is rectangular in shape with dimensions of 6.1 m in length, 0.44 m in width (width of a single channel), and 0.61 m in depth. The delta wings are in the shape of an equilateral triangle made of aluminum sheets. The delta wings are held in position, with the lower edges 3.17 cm above the channel bed. The delta wings are positioned in such a way that they oppose the incoming flow. A 16-MHz MicroADV (SonTek- a Xylem brand, San Diego, CA, USA) was used to measure three-dimensional water velocity components at various sections along the entire length of the raceway (See Figure 3). All the velocity measurements were sampled for 2 min with a sampling frequency of 50 Hz. The average water depth in the raceway was maintained constant at 20 cm for all the experiments and an operating average velocity of around 25 cm/s. An arbitrary angle of attack of 30° (assumed from the literature review and CFD simulations) and arbitrary placement of delta wings were chosen (assumed from the preliminary experiments) for this study. Optimization of the angle of attack of delta wings for vertical mixing was not performed in this study. Alternatively, for the optimization of angle of attack and spacing of the delta wings, CFD and PIV can be powerful tools for a fast approach.

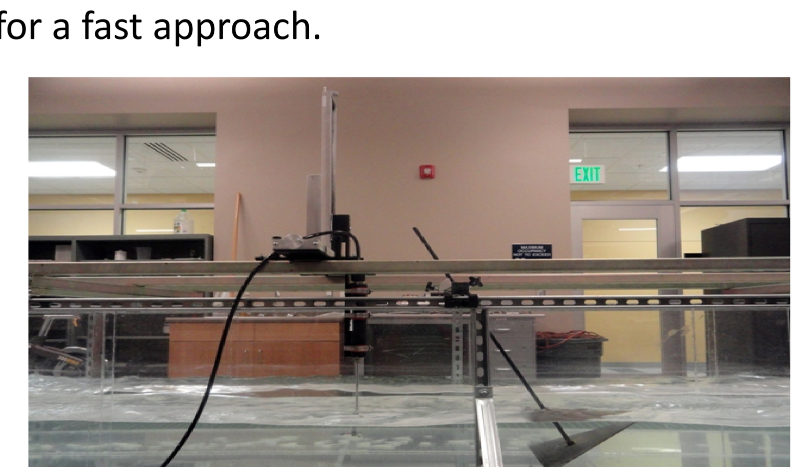


Figure 3. Photograph of ADV taking measurements in the raceway with delta wing

POWER CONSUMPTION

Addition of delta wings in the raceway will impact resistance felt by the paddle wheel due to drag losses. Power was considered as an important factor to ensure that the addition of delta wings will be an economically equivalent way of mixing. Therefore, for the addition of delta wing in the experimental raceway, the liquid circulation velocity was decreased by adjusting the paddle wheel rotational speed (See Table 1). Three sets of experiments were conducted by changing the position of delta wing. The raceway with and without delta wing was operated at two different paddle wheel rotational speeds for experiment sets 2 and 3.

Table 1. Power consumption by the paddle wheel at different conditions, ± bands indicate standard deviation of the mean power consumption

Raceway configuration	Paddle wheel speed (RPM)	Experiment set 1 power consumption (W)	Paddle wheel speed (RPM)	Experiment set 2 & 3 power consumption (W)
Without delta wing	11.5	62.07 ± 8.31	11.5	62.07 ± 8.31
With delta wing	11.5	63.91 ± 8.09	11	60.46 ± 7.19
Percent change (%)		2.96	–	-2.6

VMI ESTIMATION

A parameter is needed to quantify the vertical mixing behavior in the raceway. Vertical Mixing Index (VMI) was defined and used to compare the mixing relationships with and without delta wing in the raceway.

$$W_A = \left(\sum_{i=1}^{p} |W_p|\right)/s \qquad VMI = 100\% \frac{W_A}{U_A}$$

where p is the grid point, $|W_p|$ is the absolute value of the vertical velocity at each grid point, s is the number of grid points, VMI is the vertical mixing index, W_A is the average of the absolute value of vertical velocities at a section, and U_A is the average of the streamwise velocities at a section.

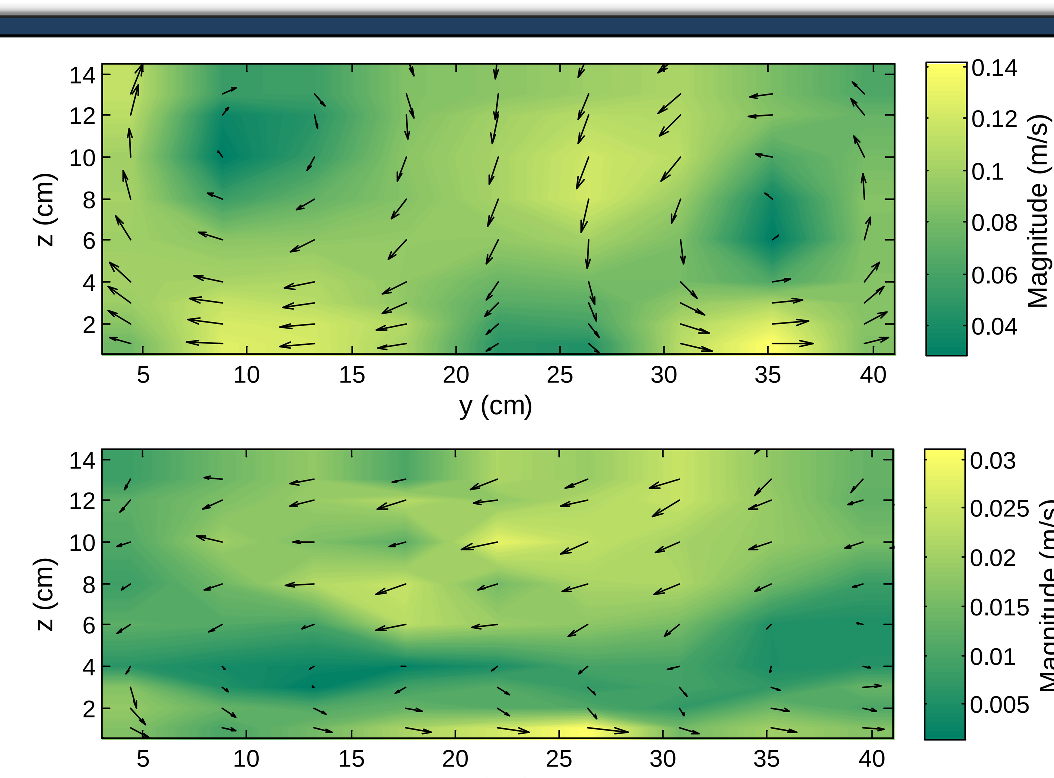


Figure 4. Planar velocity vector fields obtained at 0.46 m downstream of the delta wing (top) and without delta wing (bottom) at the same location

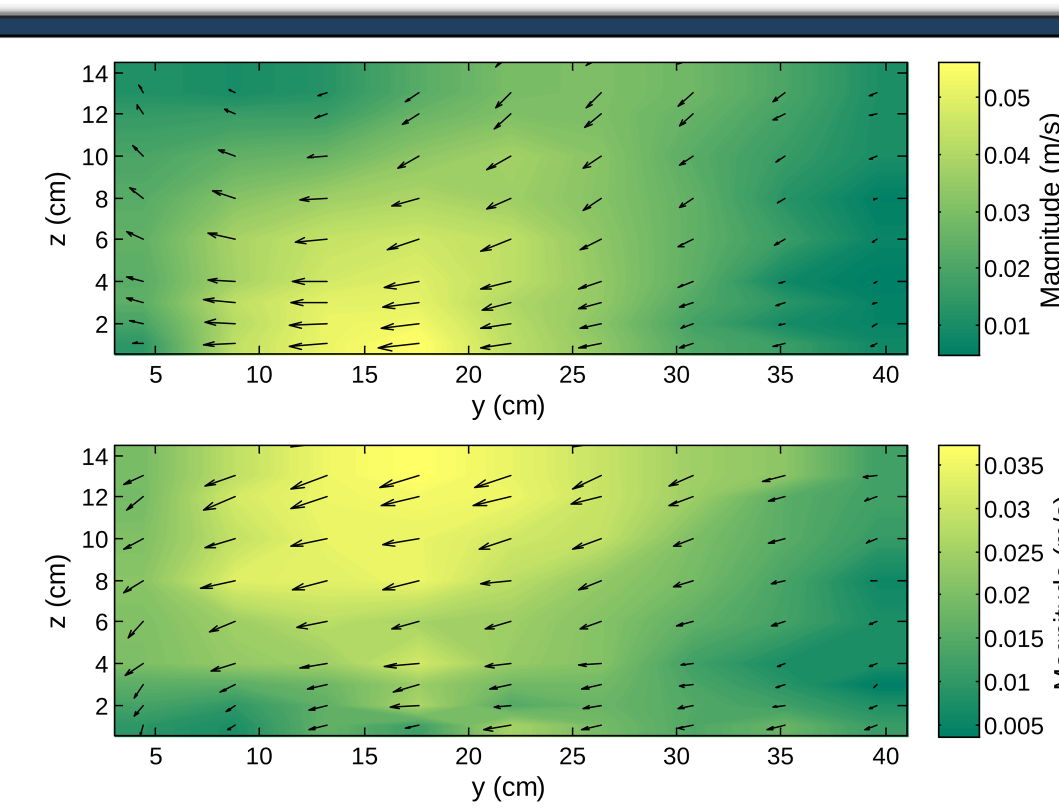


Figure 5. Planar velocity vector fields obtained at 2.99 m downstream of the delta wing (top) and without delta wing (bottom) at the same location

VMI RESULTS

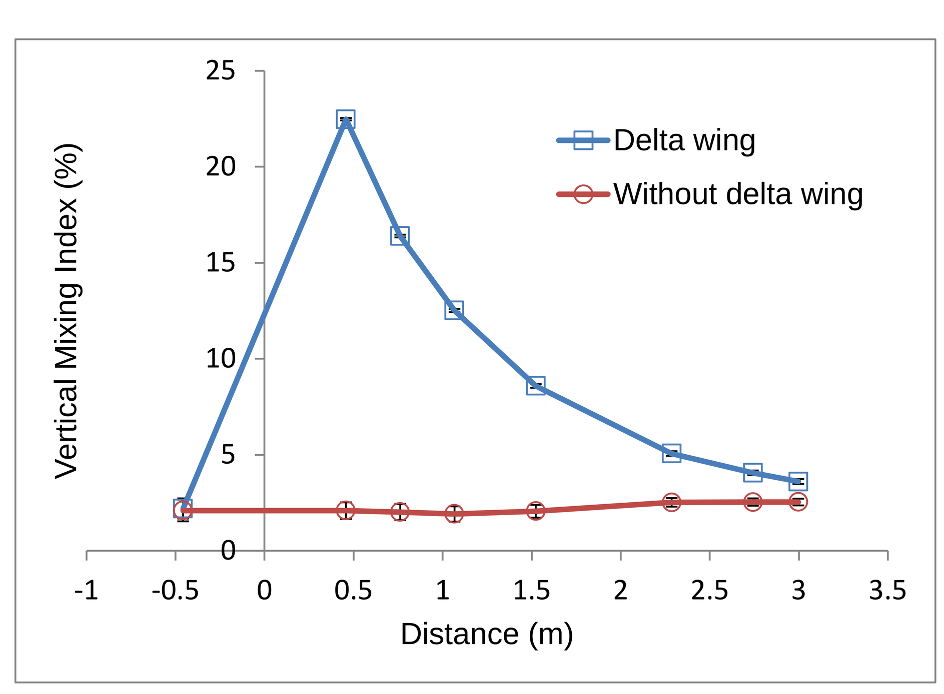
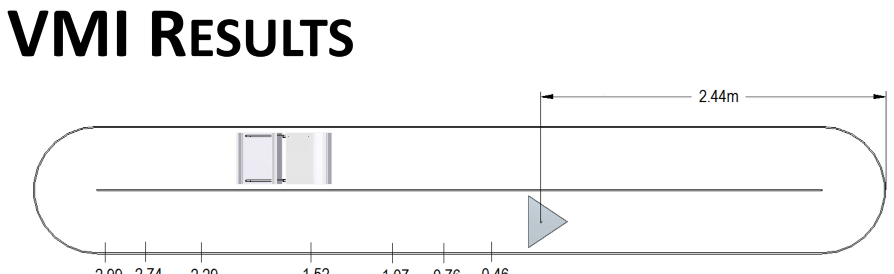


Figure 6. Comparison of VMI for the experiment set 1



Measurement locations (in m) for the experiment set 1

If the VMI is greater than 0%, this indicates the presence of vertical mixing and/or sinking of algae cells within the raceway. A VMI equal to 0% suggests that the algae cells settle towards the bottom and form sediments. The VMI provides quantitative information of these two opposing processes *i.e.* rising and sinking of algae cells. It was observed that the averaged VMI for the raceway without delta wing was around 2% (see Figure 6). An averaged VMI of 10% was reported for the raceway with delta wing in the experiment set 1. The VMI results were promising for the raceway with delta wing showing the importance of vertical mixing or circulation of the algae cells.

CONCLUSIONS

- VMI of the raceway with delta wing was significantly higher compared to the raceway without delta wing.
- The use of delta wings appears to be an effective and inexpensive way to circulate the algae cells between the bottom surface and top surface of algal raceway pond thereby increasing sunlight utilization efficiency.
- For commercial raceways, an array of delta wings will be necessary in the raceway (side-by-side and lengthwise) to satisfy the desired mixing conditions.
- To account for the impact of power consumption by the paddle wheel, the circulation velocity should be lowered with the addition of delta wings. Research is underway to determine the optimum fluid circulation velocity with delta wings.

ACKNOWLEDGMENTS

US DOE Grant No. DE-EE0003114; USTAR (Utah Science Technology and Research Initiative); Faculty, Staff, Students USU BioEnergy Center