Proceedings of the ASME 2012 6th International Conference on Energy Sustainability
ESFuelCell2012
July 23-26, 2012, San Diego, California, USA

ESFuelCell2012-91096

Study of the flow mixing in a novel open-channel raceway for algae production

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ABSTRACT

Making fuel from algae is one of the promising approaches of producing biofuels. Open channel raceway is a typical facility of growing algae in medium and large scales. The algae growth rate in water raceway is affected by conditions of water temperature, nutrients, and sunlight. These conditions are essentially associated with the fluid mixing in the flow field. A good mixing of fluid allows better diffusion of nutrients and equal opportunities of exposure to the water surface and therefore sunlight, as well as a uniform temperature everywhere in water raceway so that all algae cells grow in the same rate. While a better fluid mixing is benefit to the growth of algae, it is also desirable that the energy needed to drive the flow and mixing being the minimum. In this work, a novel flow field has been proposed and the flow field was studied through flow visualization and CFD analysis. Optimization of the flow field for better flow mixing and low energy cost for the flow has been considered.

INTRODUCTION

The global demand for energy has risen dramatically in recent years. But the world continues to rely heavily on fossil fuels, which is less and less available although not immediately. Also, the global warming as a consequence of CO_2 emission is another big issue to our environment. Renewable energy with low carbon emissions, such as biofuels, wind energy, and solar energy, can alleviate the pressure on the demand of fossil fuels as well as the global environment [1].

Biofuel is a nontoxic and biodegradable alternative fuel that is obtained from renewable sources [2]. Extracting biofuel from algae is expected to produce transportation fuels. The carbon fixation by algae is also a very effective method to remove CO_2 from the global atmosphere. When the biofuels are oxidized, CO_2 can be recycled from the atmosphere through photosynthesis. So getting biofuel from algae is a significantly benign technology that can benefit our planet [3].

The growth of algae strongly relies on some external conditions, such as nutrients, temperature and sunlight, and also algae typically grows within a few centimeters of the water surface. Therefore, mixing in water has a strong influence on the rate of algae growth [4]. Good mixing always leads to a higher growth rate because of a uniform concentration field of nutrients and equal opportunities of exposure to sunlight. Improving the ability to model the effect of mixing on algae growth could result in better models for marine ecosystems and global climate change, as well as improved ability to design commercial algae farms to optimize algae production rates.

Fig. 1 Conventional algal raceway pond (Photo credit: Seambiotic, Ltd. [5] *)*

Conventional raceway pond [5-10] uses a paddle wheel to strengthen flow mixing by disturbing the water, but it still has the disadvantages of insufficient flow mixing and temperature control, which will lead to low algal production.

To overcome the weakness of conventional raceway, a novel flow field of algae raceway has been proposed in this paper. The new raceway has a slope and water flows down driven by gravitational force. By installing some baffles in the algal water raceway, not only the water retention time can be extended, but also the mixing can be enhanced, which will bring about the uniform nutrients concentration field. Presented in this paper is the study for the novel algae raceway through flow visualization and CFD analysis based on a small scaled table-sized testing system. The optimization for better mixing and low energy cost is also considered.

CONFIGURATION OF NOVEL RACEWAY FLOW FIELD

From the flow field perspective, three basic points will be beneficial to algal production and less energy cost: (1) better flow mixing by tumbling (up and down) the algae cells for more chances to absorb nutrient and sunlight; (2) a declined slope by utilizing the gravity force to drive water in the raceway to a water reservoir; (3) a good retention time of water in the raceway in one run for better absorption of nutrients.

Following these considerations, an algal raceway having a slope was proposed by the research team. The flow field in the raceway is managed to be serpentine by setting some baffles (or dams) on the bottom. This helps the system to have a longer retention time for algae to grow. Furthermore, the cross flow that climbs over dams and the main serpentine flow in the channel between two dams will give rise to a spirally forwarding flow, which can make the nutrients reach to all algae cells from bottom to top in flow channels. This expected flow pattern is illustrated in Fig. 2.

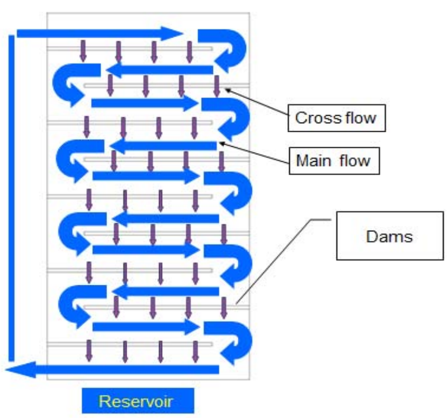
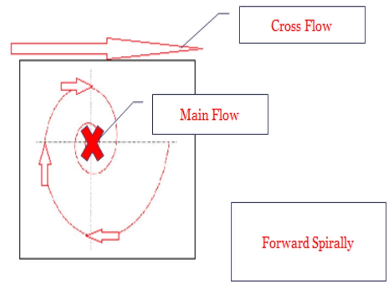


Fig. 2 (a)



(b)

Fig. 2 Schematic of novel raceway flow field design (a) Novel flow field design; (b) Cross-sectional view of flow field

EXPERIMENTAL SETUP

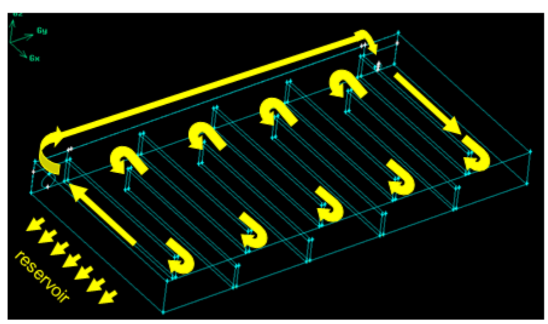
Based on the open channel shallow water assumption the channel width and the depth of water should have

$$W / D \geq 5 \tag{1}$$

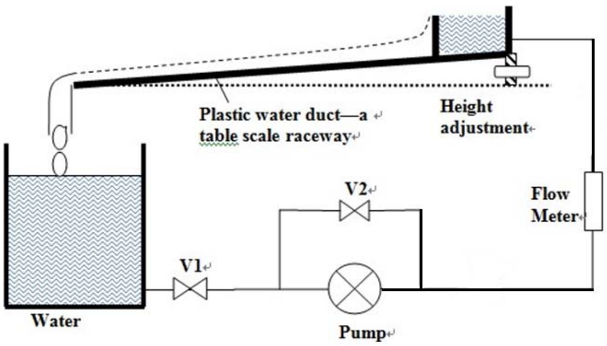
where W is the channel width, D is the water depth (which is determined mostly by the height of the dams here in this design). Considering the dimensions of the whole system, the algae raceway has 6 flow serpentine channels and 5 dams, which keeps the ratio W/D greater than 5. So if we scale up this system to a big raceway, the flow field will be similar as it is in this small test system.

Test system

The setup of test system is shown in Fig.3. The system consists of a plastic table-sized raceway with a water reservoir and a slope adjustment for the raceway. The water is circulated by a pump. Two ball valves and a flow meter were in the loop to facilitate the flow control and measurement. Plexiglas plates in thickness of 1.27 cm were used to build this small scaled raceway. The raceway has dimensions of 1.4m long and 0.7m wide. The boundary outer walls are 12 cm high. The water depth of the test system can be controlled by choosing different number of dams, and also the cross flow can be controlled by varying the height of dams.



(a)



(b)

Fig. 3 Schematic of the table-sized raceway and test system setup. (a) Raceway model; (b) Test system setup

Instrumentation for this experimental setup is required to measure the flow rate, the water velocity in channels, and visualization of flow mixing at various conditions. The centrifugal pump can provide a flow rate in a maximum of 70L/min, and the slope has the ratio of 1:100, which simulates the slope of an outdoor field raceway. A water velocity meter shown in Fig. 4 was used, which has an accuracy of 0.01cm/s.

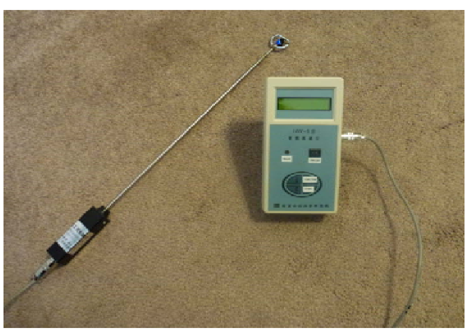
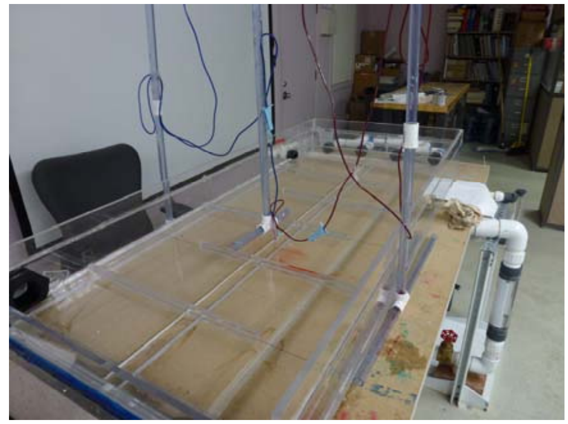


Fig. 4 Water flow velocity meter

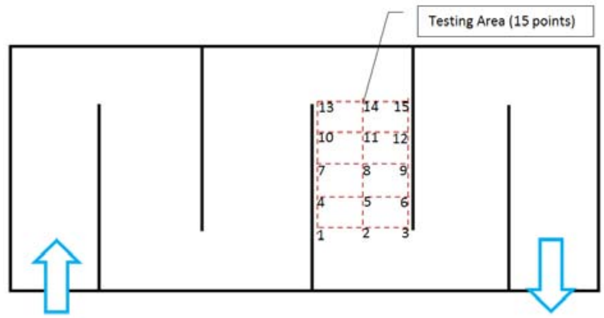
Flow visualization

The visualization of the flow field is to obtain a qualitative understanding to the flow mixing in the raceway flow field. A steady state flow field was maintained and the flow in the fourth channel was chosen to visualize. At the required locations, color ink was injected using a very fine syringe to the middle of the height of the water. Visualization is from the transparent side walls of the raceway. Totally 15 points were selected for flow visualization as indicated in Fig. 4 for the locations.

The flow rate was controlled to be 24 L/min. A pipe of inner diameter of 25.4 mm feeds water to the raceway, and the water outlet pipe has an inner diameter of 50.8 mm. The velocity at the feed pipe is 0.1m/s. Together with the flow visualization, measurement of water velocity and water depth was also conducted.



(a)



(b)

Fig. 4 Raceway and locations of visualization and test (a) Flow visualization setup; (b) 15 test points in the 4th channel.

Red and blue ink (food dye) was used to observe the spread of the ink due to the flow field. The ink injection lasted for 10 second. Seeing through the side wall of the raceway, photos were taken at a time point of 10 second after the ink injection started. It is easy to understand that good mixing should indicate a well spread of the ink during a same period of time. All the photos were taken under the same visualization condition so that the flow mixing can be compared between cases of different flow rate and raceway structures. The visualization was done one location at a time.

Two designs of raceways have been chosen for the tests and comparison for optimization. The dimensions of the channels and dams are shown in Table1. Visualizations and tested data at 9 points of locations (1, 2, 3, 7, 8, 9, 13, 14, 15) are to be presented.

Table 1 Dimensions of two sets of tests

Test Sets	W/D	W (mm)	D (mm)	G/W
Set 1	6	220.63	36.77	0.8
Set 2	5	220.63	44.10	0.8

Note: G is the gap between the dam end and the raceway sidewall

CFD ANALYSIS

CFD was applied to analyze and optimize the raceway design. The commercial software ANSYS Fluent@ 6.3 was chosen for the study. Based on the visualization of the flow field, the Set 2 raceway design was studied in the simulation, as this design showed a better flow mixing.

Governing equations

The flow in raceway is a shallow water flow. Therefore, the CFD analysis used three-dimensional Navier-Stokes equations for laminar flow. The flow is incompressible, unsteady, and has constant properties.

The continuity and momentum equations are

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0 \tag{2}$$

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_j}+g_i+\upsilon\frac{\partial^2 u_i}{\partial x_j^2} \tag{3}$$

The boundary conditions are:

Wall: $u_i = 0$ (4)

Free surface: $\frac{\partial u_i}{\partial z}=0$, $p = p_0$ (5)

Depth of the computational domain is 9 cm including water and air. The depth of water is around 7 cm according to the experimental observation.

The studied inlet velocities are

$$u = 0.08m/s,\ 0.10m/s,\ 0.12m/s,\ 0.14m/s$$

The selection of these velocities referenced to the studies by Richmond and Vonshak [5]. They observed that when the mean flow velocity was around 0.125 m/s, the algal production rate could be 50% higher than static pond. Many researchers have reported that the water velocity is associated with the flow mixing. In some sense the mixing can be managed simply by adjusting the fluid velocities in a raceway [6].

Numerical model for free surface flow

To treat the free surface of water flow, VOF (Volume of Fluid) model was used in this simulation. The VOF model can simulate multiphase flow in Fluent@, and it is especially useful to trace the free surface in the computational domain.

The flow in the experimental test is laminar, but may close to the transition to turbulent flow. In this preliminary study, the flow was treated as laminar flow. The flow in actual raceway can go to turbulent region and thus turbulent flow model and simulation will be conducted in the near future.

Computational procedures

Following the standard steps of using ANSYS Fluent@, the computational domain was generated using Gambit@. VOF model was chosen in the computation. The computed four cases were listed in Table 2, where velocities are from the water feed pipe. In the post-computation data process, the velocity field, particularly the spirally forwarding vortex was hoped to be observed.

Table 2 Cases studied in CFD

Case Number	Case I	Case II	Case III	Case IV
Inlet Velocity (m/s)	0.08	0.10	0.12	0.14

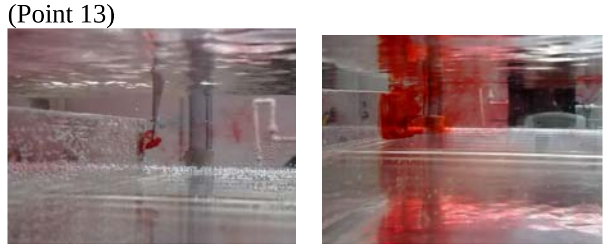
RESULTS AND DISCUSSION

In this section, the flow visualization results and computation results will be presented and discussed.

Flow visualization results

The pictures shown below, in Fig. 5, are from the visualization from 9 of the locations as indicated in Fig. 4. Pictures on left side are from raceway Set 1, and the ones on right side were from the raceway Set 2. The locations of the visualization point are also noted for the photos.

(Point 13)



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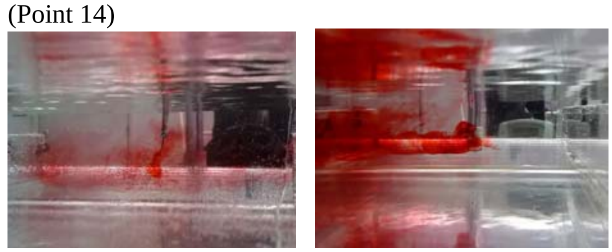

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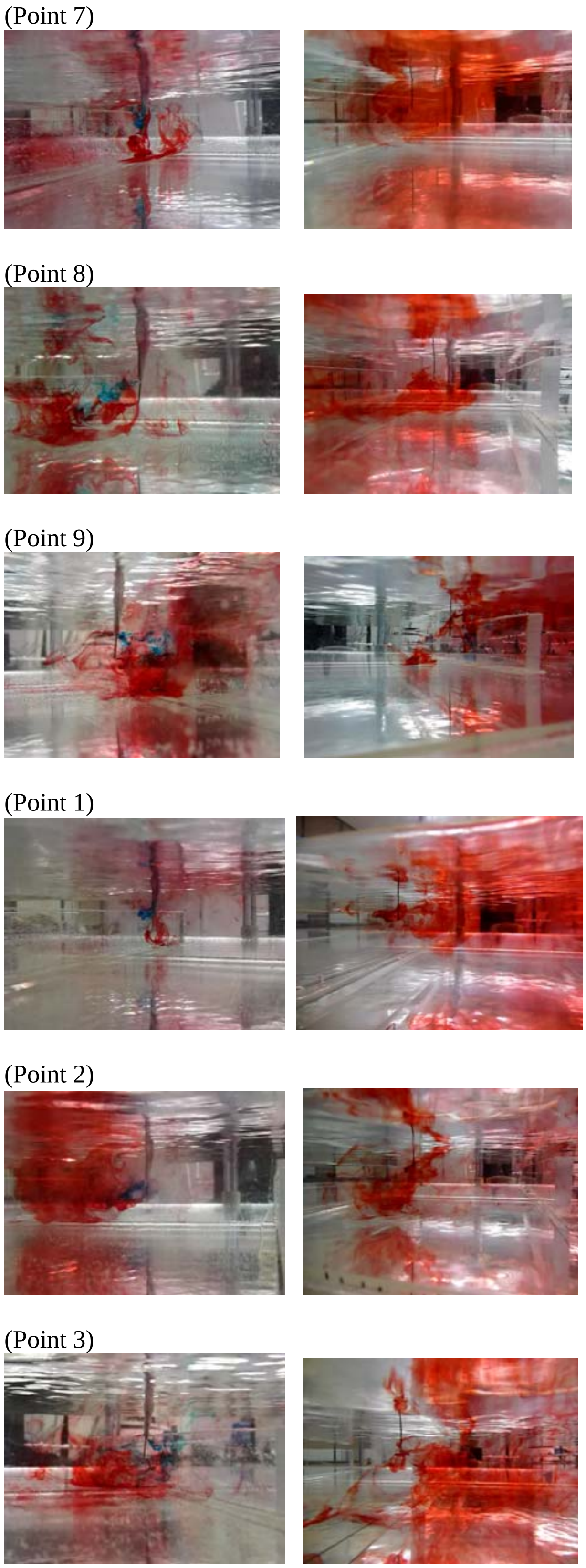

Fig. 5 Flow visualization test results
(Note: W/D of left column is 6 and right column 5)

A good mixing of the flow will demonstrate a relatively larger area of dissipation of the red color. There are two important aspects to observe from the visualization—the comparison between different locations in one raceway, and a comparison of the same location between two raceways. It is also important to observe whether there is mixing between the main flow in the channel and the climb-over flow.

From comparison of the two raceways, it was found that the flow mixing at the observed locations in the raceway Set 2 was better than that in raceway Set 1, in general. The two test cases had the same flow rate. In raceway Set 2 the dam height was larger. It was observed that the climb-over flow was not very strong , but the climb-over flow and main flow interacted very well. In the raceway Set 1, the dam was lower and the climb-over flow was strong. However, it did not interact well with a relatively weak main flow.

Comparing to the photos from locations 1, 7, 13 of the same raceway Set 1, it was seen that the flow mixing in point 7 was better than the other two points 1, and 13. Point 13 had rather weak mixing in this case. It was observed that in the raceway Set 1, the main flow was relatively weak and most water flows due to the climb-over flow. Comparing the photos for raceway Set 2, it was seen that the flow mixing at all points are rather good.

These two raceways held the same channel width. One more parameter to exam is the total length of the channels, which determines the retention time of the algae in raceway. In the two cases the total length of the channels are the same. Therefore, the difference of the flow mixing performance told us that the dam height played a significant role in determining if the mixing was good or not.

From the overall observation, it may be concluded that the flow mixing in the raceway Set 2 is better under the same flow conditions except for the dam height. We expect the better algae production also in this raceway.

Flow velocity test

The main flow velocities at the locations indicated in Fig. 4 were measured at the half height of the water depth for the raceway Set 2. The velocity profiles are shown in Fig. 6. We can see the velocity profile shift. At locations (13, 10, 7, 4, 1) behind the front dam, the velocity is high at point 13 and then gradually decrease. The main flow decelerates near this wall. At locations (15, 12, 9, 6, and 3) in front of the other dam of the channel, the velocity increases from low at point 15 to high at point 3. The flow accelerates from point 9 to point 13. Because at point 9 the flow velocity stops decelerating and starts to accelerate, and therefore the main flow at this point could be weak and the climb-over flow can be relatively strong. The flow mixing in the deceleration zone could be slightly week.

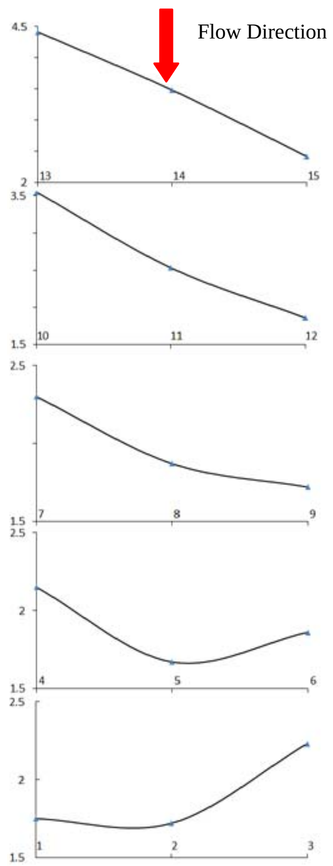

Fig. 6 Velocity test results at different locations

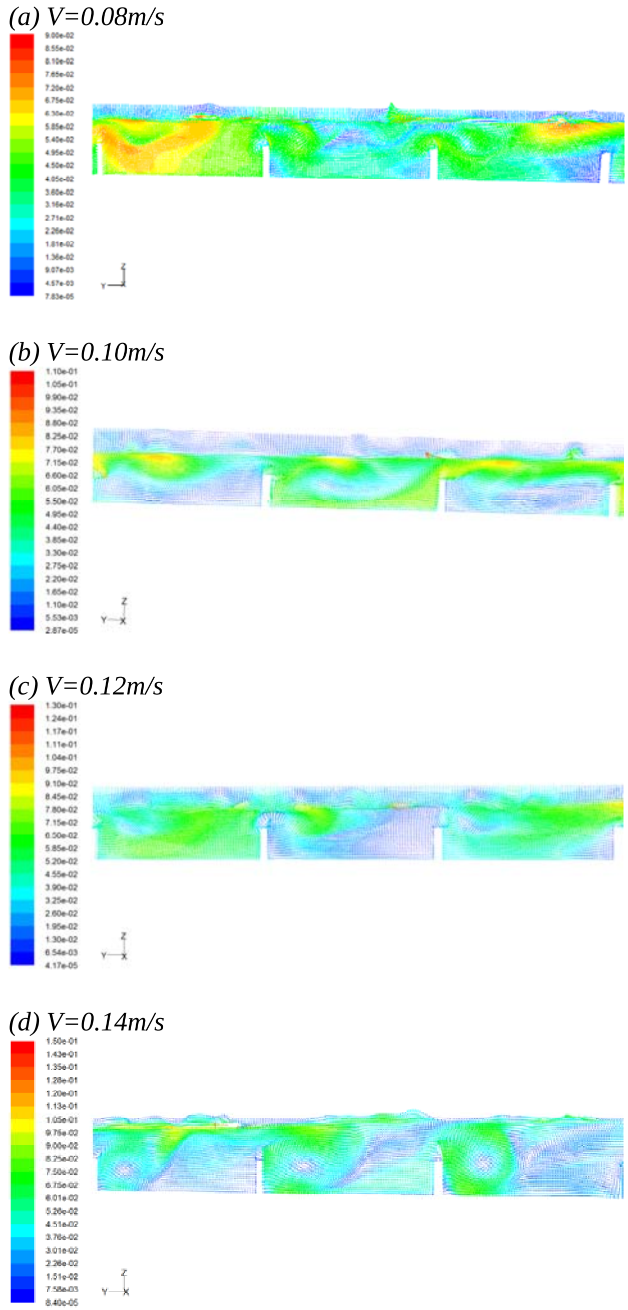

Fig 7 Flow velocity vector at the middle-line cross-section

Numerical results

The current CFD analysis studied four cases different in inlet velocities in the raceway Set 2. The simulation results are to be examined to verify the expectation that the flow fields due to the novel design of the raceway will show a spirally forwarding vortex in the main flow direction or the cross-section in the length direction of the raceway.

Figure 7 shows the velocity vectors on the cross section along the mid-line of the width of the raceway for three serpentine channels, 3, 4, and 5. Number 4^{th} channel is also the channel where flow visualization and flow velocity measurement were conducted.

The computational domain includes water and a thin layer of air. Therefore, there is a visible interface in the graphs of the velocity vectors. For example, in Fig. 7 (a), (b) and (c), the interfaces are very clear, on top of the interface is actually airflow which has a very low velocity, and below that is water flow. In Fig. 7(d) the airflow layer is rather thin due to the high water flow rate which takes a major part of the thickness in the computational domain.

There are three points worth observing from the velocity fields shown in Fig. 7. First the flow that water climbs over the dams is clearly seen, which agrees with the observation in the experiment. When the raceway inlet flow velocity is low, the climb-over flow is significant but the main flow is weak, which does not create a strong spirally forwarding vortex, as seen in Fig. 7(a). With the increase of the inlet flow velocity, the interaction between the climb-over flow and the main flow becomes significant and there are clear vortexes behind the dams as seen in Fig. 7 (d). The vortexes promote the up-and-down type of motion which is believed beneficial for algae to surface up and get sunlight [11-15]. Nevertheless, the flow mixing in Fig. 7 (b) and (c) shows to be significant and therefore should be suitable for algae growth.

CONCLUSION

In this paper, a novel flow field design of open-channel raceway for algal growth has been proposed, which was then studied by experimental visualization and CFD analysis. The basic proof-of-concept has been successful. Some conclusions are drawn as follows:

(1) Flow visualization tests were conducted on a small scale raceway pertained to the novel design. The flow and mixing of two test models different in the height of the dams were visualized. It was found that the height of the dams significantly influence the flow mixing. One raceway model Set 2 was considered to be a better choice for its good flow mixing under the same flow rate.

(2) Velocities of the water flow were experimentally tested. The velocity profiles in a flow channel showed variations of the flow velocities and the main flow deceleration and acceleration zones could be mapped out, which helps a better understanding to the flow field.

(3) CFD study was conducted to verify the basic flow field structure as expected for the novel raceway design. The study used VOF model and discovered some details of the flow field structure. The results qualitatively agree with what observed in the flow visualization.

(4) The investigations in this work are seen as preliminary studies. Although more detailed work needs to be accomplished, such as simulation with turbulent models, the optimization of raceway dimensions etc., the simulation successfully proved the basic hypothesis of the design concept for the novel algae raceway.

(5) Simulations and test of algae growth in the novel raceways will be conducted in the near future.

ACKNOWLEDGEMENT

The authors are grateful to the support by the US Department of Energy. Thanks are also due to Dr. Randy Ryan, Mr. Said Attalah, Professor Chris Choi in Department of Agriculture and Biosystem Engineering at the University of Arizona for their help and valuable discussions.

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