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Particle Image Velocimetry Measurement of Hydrodynamic Properties of Raceway Pond with the Effect of Central Wall

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Raceway ponds with paddle wheel mixing are the most common choice for microalgae cultivation because they allow better interaction of algae cells with water, nutrients, and CO_2. A central wall splits the algal pond into two channels, which significantly affects hydrodynamic properties of the pond. This study used the particle image velocimetry (PIV) technique to experimentally investigate the effects of the central-wall-end designs on the fluid properties of a laboratory-scale raceway pond. The rectangular and round ends of the central wall were compared using a velocity field, the Reynolds number, power consumption, and microeddy length. Flow circulation was found to be more effective in the round end model because of the smaller recirculation size and smaller dead zones. Mixing was improved by using a central wall with round ends. Power consumption was influenced by velocity, and the round-end model consumed less power during mixing. Higher turbulent mixing resulted in shorter microeddies that could damage the boundaries of the algae cells.

1. Introduction

Paddle-wheel-driven open raceway ponds are widely used for microalgae cultivation because the ratio of their biofuel yield per hectare to land use is higher than that of other traditional biofuel resources.(1) The mixing system used in raceway ponds affects not only manufacturing costs but also the distribution of nutrients, CO_2, and sunlight, to the microalgae cells.(2) Paddle wheels are commonly used as mixing devices in open raceway ponds to generate the necessary water velocity and ensure effective mixing in the pond channels. Uniform flow mixing by a paddle wheel is necessary to bring the algae cells from the bottom to the top surface of the pond and expose them to sunlight. The turbulent mixing generated by the paddle wheel also enhances the transfer of nutrients from the water to the algae cells by damaging their cell membranes.(3)

Paddle wheels produce a pulsating velocity in an algal pond, and typical water velocities suggested for the effective mixing of microalgae are in the range of 0.1–0.5 m/s. The water depth in the algal pond must be within the range of 0.1–0.15 m for efficient distribution of sunlight to all microalgae cells.(4,5) Richmond and Hu(6) used the Reynolds number (*Re*) to define mixing in the

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algal pond. A high level of mixing indicates a high *Re*, whereas low-level mixing is associated with a low *Re*.[6] Several researchers have associated mixing phenomena in the pond with the stirring rates (rotational speeds) of the paddle wheel. The productivity of the algae cells increases with increased paddle wheel rotational speeds because of high-turbulence mixing.[7] In addition to stirring rates, hydrodynamic properties are also affected by the geometrical features of algal ponds (i.e., a central wall and baffles). These features are important in the design of algal ponds because they may influence power consumption and distribution of nutrients and sunlight to algae cells.[8] Cheng *et al*.[9] used up-down chute baffles to boost the penetration of sunlight to the bottom of an algal pond by enhancing turbulent flow via the generation of liquid vortices. The baffles significantly increased the biomass volume by decreasing the dark-light cycle caused by higher turbulence.[9] Huang *et al*.[10] also used baffles and flow deflectors to increase turbulent mixing and decrease power consumption of the raceway pond. They reported that a raceway pond with baffles and flow delfectors increased the average flow velocity, reduced power consumption, and enhanced vertical light distribution.[10]

However, increasing the water velocity can damage the mechanical structure of algae cells because of higher fluid shear forces. Camacho *et al.*[11] stated that higher stirring rates increase turbulent flow. The return damages algae cells because of hydrodynamic stresses.[11] The performance of mixing can be analyzed by computing the hydrodynamic properties of the pond (Reynolds number, dead zone areas, and shear rate) that are significantly influenced by the pond geometry.[12,13] With advancements in computational fluid dynamics (CFD) codes, modeling hydrodynamic flow conditions under the influence of various geometrical features is now possible. Numerous numerical studies have been conducted to observe the effects of various central wall designs on the flow-mixing of algae cells in raceway ponds.[14–16] Hreiz *et al*.[17] compared experimental and CFD hydrodynamic results with the effect of various paddle wheel blade configurations.[17] However, experimental research on the effects of the geomery of the central wall on the hydrodynamic characteristics of an algal pond is uncommon. Therefore, optimization of the algal pond design and validation of past simulation studies are necessary.

This study aimed to experimentally investigate the effects of various designs of central-wall-ends on fluid dynamic characteristics using the particle image velocimetry (PIV) technique. We used two different shapes of central wall ends (i.e., rectangular and round). Initially, the flow was visualized using the rectangular end. The round end was then used to observe the central wall's effect on water flow. Velocity field, power consumption, and microeddy length were used to compare the rectangular and round ends of the central wall and optimize the pond design. The Reynolds number was also used to examine the mixing of algae cells in the pond with the central wall.[6]

2. Materials and Methods

2.1 Raceway pond

An acrylic 0.1 m^2 laboratory-scale raceway pond with a length (L) of 0.5 m, a width (W) of 0.2 m, and a height (H) of 0.15 m was used for the PIV experiment (Fig. 1). The water height (d) in the pond was maintained at 0.1 m during the flow visualization experiment. A paddle wheel composed of six blades with a diameter of 0.1 m was used to generate the pulsating flow in the pond channels. The paddle wheel blades were 0.10 m long and 0.025 m wide. The paddle wheel was placed at a

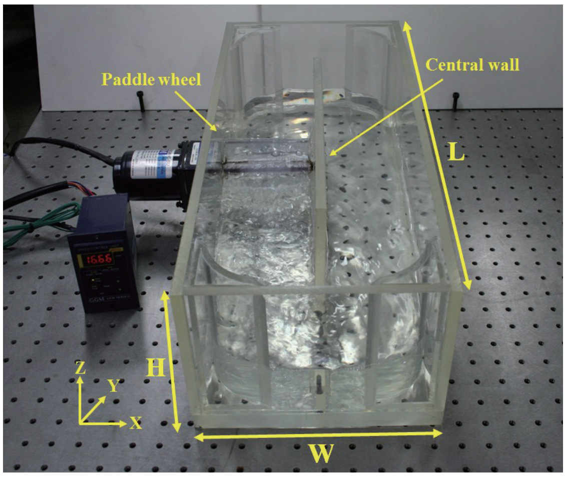


Fig. 1. (Color online) Laboratory-scale raceway pond with surface area of 0.1 m^2.

distance of 0.2 m from the wall of pond in the upstream channel. A motor with a rotational speed of 500:24 and gear ratio of 7.5:1 was used to provide the paddle wheel with the necessary speed to cause water circulation in the pond. The central wall of the pond with rectangular and round ends is shown in Fig. 2. The study used the hydraulic diameter (D_h) to calculate *Re* and observe mixing in the tank:

$$D_h = \frac{4WH}{(2H + W)}, \quad (1)$$

and

$$Re = \frac{\rho \times D_h \times V}{\mu}, \quad (2)$$

where W and H are the width and height of the pond, respectively; ρ is the water density (1000 kg/m^3); μ is the water viscosity (0.001 Pa·s); and V represents the average fluid velocity in m/s.

Hydraulic power refers to the power required to mix the water in the raceway pond; it depends on the flow rate and head loss in the algal pond. The following relation was used to calculate the hydraulic power and observe the effects of rectangular and round ends of the central wall on power consumption:[4]

$$P_h = \gamma n^2 V^3 d^{-0.33}, \quad (3)$$

where P_h is the power consumption (W/m^2), γ represents the specific weight of water (9810 N/m^3), n is the roughness coefficient (0.009 for acrylic), V is the average velocity (m/s), and d is the water depth (0.1 m).

Camacho *et al.*[11] reported that high turbulence created by the paddle wheel may damage the membranes of the algae cells. Therefore, to observe the effect of turbulence on the algae cell

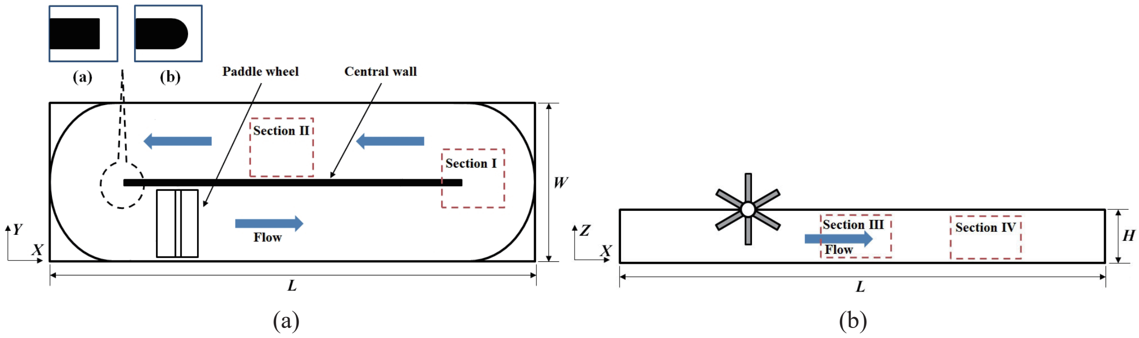


Fig. 2. (Color online) 2D schematic view of the pond: (a) top view (*XY*-plane) and (b) side view (*XZ*-plane).

structure, Kolomogorov's theory was used to estimate the length of the turbulent eddy in the pond. A microeddy length (λ) less than or equal to the cell dimension (100 µm) will damage the algae cell structure:(11,18)

$$\lambda = (\mu^3/\varepsilon)^{1/4}, \tag{4}$$

$$V = (\varepsilon\mu)^{1/4}, \tag{5}$$

where λ is the microeddy length (µm), μ represents the water viscosity (0.001 Pa·s), ε is the turbulent energy dissipation rate (W/kg), and V is the average velocity (m/s).

2.2 PIV experiment

PIV has become the main technique for flow measurement because it can measure an entire two-dimensional or even three-dimensional velocity field simultaneously, unlike other traditional methods (hot-wire anemometer, laser Doppler anemometry, and phase Doppler particle analyzer) that can only detect velocity at a single point. PIV is a robust technique that offers better resolution, and flow properties are easily measured without flow field disturbance.(19,20) Tracing particles are added to the working fluid and are illuminated by a laser beam. The position of the illuminated particles is captured with a high speed camera, and the velocity vector field is generated after postprocessing.

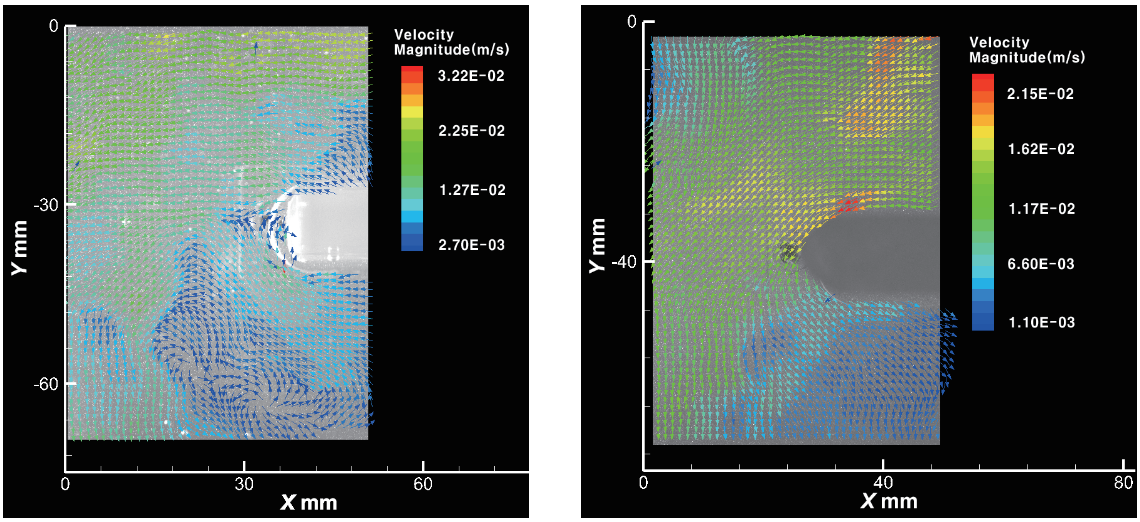
A two-dimensional PIV system was used in this experiment. The system consisted of an Nd:YAG dual-head laser source, a lens set, CCD camera, synchronizer, image frame grabber, and a computer. Tracer particles with a diameter of 15 µm and a density of 1.1 g/cm^3 were added to the pond for flow visualization. The CCD camera utilized a spatial resolution of 2K × 2K pixels to obtain an image of the tracing particles. A low pass filter and a Q-switch with a wavelength of 532 nm were connected to the CCD camera. The low pass filter increased the contrast between the acquired image and the background. The CCD camera captured two frames in double exposure mode using an image grabber with a delay time of 5 ms. The shooting distance was set to five pixels/shot for better images of the tracing particles. The coordinate system of the algal pond for the PIV experiment is shown in Fig. 1. PIV experiments were conducted using the central wall with rectangular and round ends. The effects of the central wall on the fluid field in the pond were observed by selecting two sections to measure fluid velocity (Fig. 2). Section I was located in the upstream channel around the end of the central wall (X = 0.42 m, Y = 0.11 m), and Section II was located in the downstream channel (X = 0.2 m, Y = 0.07 m). Section III (X = 0.2 m, Z = 0.075 m) and Section IV (X = 0.37 m, Z = 0.075 m) were selected for the observation of paddle-wheel-mixing effects in the vertical direction (XZ-plane). All PIV experiments were conducted at room temperature.

3. Results and Discussions

3.1 Velocity field and streamlines

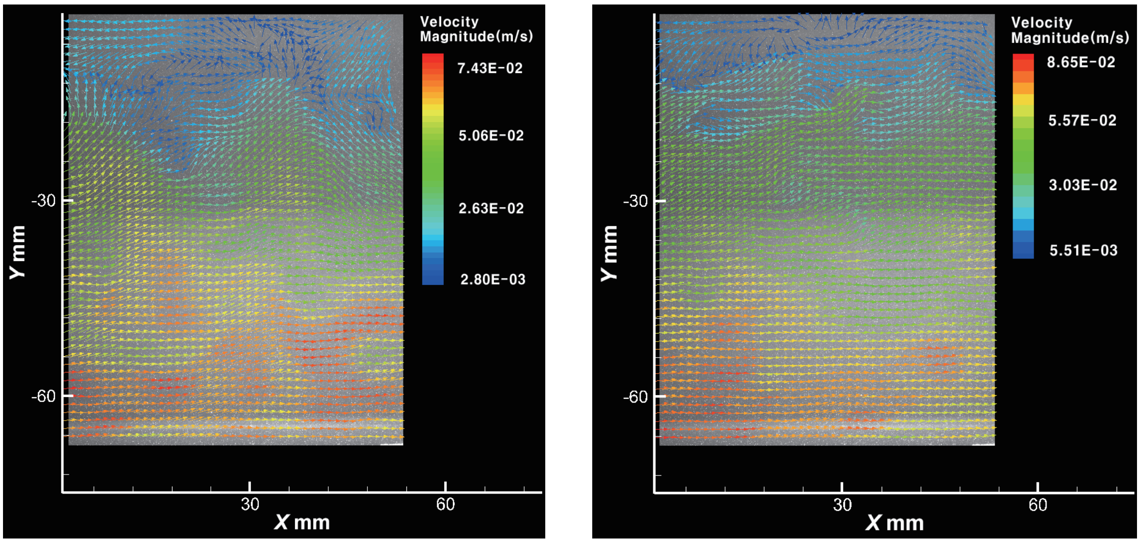
The velocity field in Section I (XY-plane) around the rectangular and round ends of the central wall is shown in Fig. 3. Results were computed at a paddle wheel rotational speed of 16. The flow particles failed to follow the geometrical shape of the rectangular end and recirculation zones formed [Fig. 3(a)]. These recirculation zone formations near the rectangular end of the central wall have reduced velocities and are called "dead zones". The algae cells tended to accumulate in these low velocity areas (dead zones) resulting in lost algae culture because of anaerobic conditions and consequently reducing biofuel production.[21] The round end model displayed different flow characteristics. The fluid particles followed the geometry better than did the former model, and dead zones were minimized [Fig. 3(b)]. These results show that a streamlined structure helps the fluid remain intact within the structure, thereby reducing chances of flow recirculation.

Figure 4 shows the velocity field in terms of streamlines and vector plots for Section II. The velocity gradient dropped significantly, and more recirculation zones were formed under the rectangular end of the central wall [Fig. 4(a)]. The decreasing velocity increased the dead zones, which will have a negative effect on biofuel production because of the reduction of photosynthesis.



(a) (b)

Fig. 3. (Color online) PIV images of flow fields in Section I (XY–plane) with (a) rectangular and (b) round central wall ends.



(a) (b)

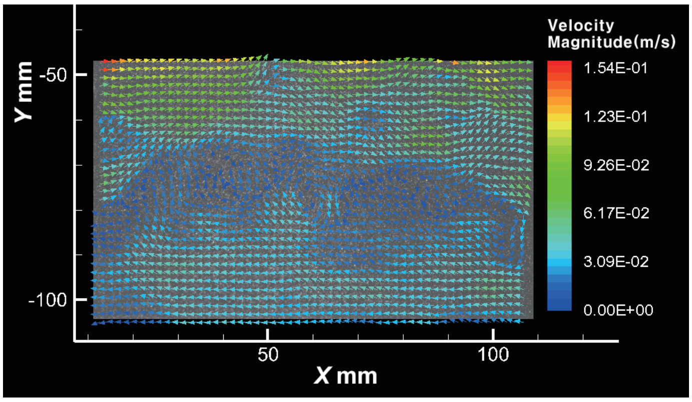
Fig. 4. (Color online) PIV images of flow fields in Section II (*XY*-plane) with (a) rectangular and (b) round central wall ends.

Higher velocities were also observed in the mid-section of the channel with a rounded central wall end, indicating the presence of more uniform mixing in the pond [Fig. 4 (b)]. These results suggest that the central wall with a rectangular end reduced water velocity in the pond channels, which will impair proper circulation of algae cells in the pond, and thus degrade their interaction with nutrients, CO_2, and sunlight. Water circulation may be increased by using higher paddle wheel rotational speeds, but high turbulence could damage algae cells.(11) Therefore, using an algal pond with a round end central wall may increase biofuel production because it can generate uniform water circulation.

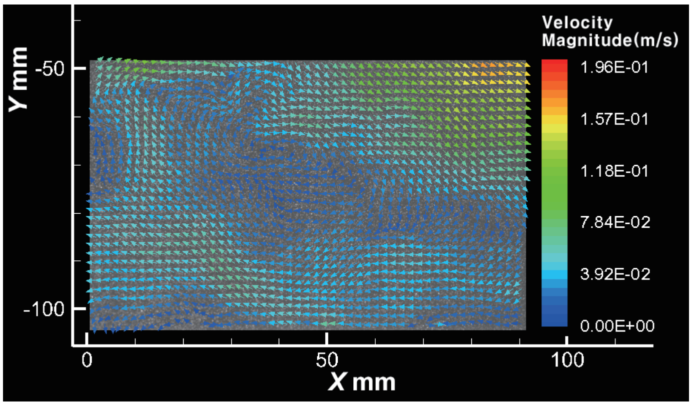
The velocity field was also measured in Sections III and IV to observe paddle wheel effects on the velocity gradient and recirculation zones in the depth direction (Fig. 5). The effect of the paddle wheel was more prominent in Section III because this section was located near the paddle wheel. Therefore, the average velocity gradient was higher in this region than in Section IV. A large volume of dead zones was formed at the bottom of the pond in Section IV [Fig. 5 (b)]. Algae cells accumulated in this area because water circulation was minimal, reducing algae productivity.(21) Section III resulted in more uniform vertical water circulation because of the greater effect of the paddle wheel in this area. This implies that the interaction of algae cells with nutrients, CO_2, and sunlight, increased in Section III.(2)

3.2 Turbulent mixing

The *Re* was used to determine mixing intensity for both rectangular and round ends of the central wall.(6) Figure 6 shows the value of the local *Re* in Sections I and II at minimum, median, and maximum flow velocities. Results were computed using a paddle wheel rotational speed of 16. The value of *Re* depends on the flow velocity. Its value is therefore high at maximum flow velocity and low at minimum velocity. The water mixing intensity in the pond is higher at maximum flow



(a)



(b)

Fig. 5. (Color online) PIV images of flow fields in (a) Section III and (b) Section IV (*XZ*-plane).

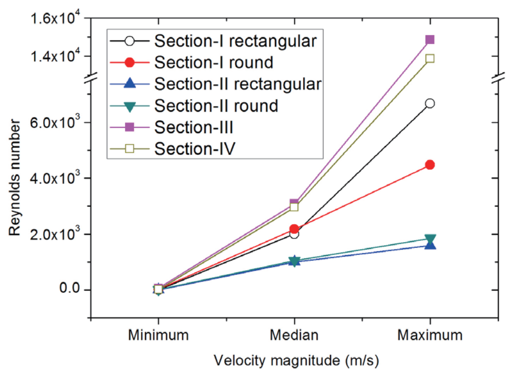


Fig. 6. (Color online) Effect of rectangular and round ends of the central wall *Re*.

velocity, thereby enhancing the interaction of algae cells with nutrients and CO_2, consequently improving biofuel production.[2,3]

The turbulent mixing intensity was higher in Section I than that in Section II because the former was located nearer to the paddle wheel. The rectangular end resulted in a higher mixing intensity because its sharp edges increased the velocity and the *Re*. High turbulent mixing may damage algae cells by harming their membranes.[11] Sharp edges also created larger recirculation zones in the downstream channel, which reduced the *Re* in Section II. The flow was more streamlined in the case of the round end model. Thus, the mixing phenomena was higher than that in the rectangular end in Section II because of decreased vortex flow. These results suggest that the round end model produced uniform mixing in the pond. The turbulent mixing in Sections III and IV was also estimated to evaluate the paddle wheel mixing in the vertical direction. Mixing is higher in Section III because it is located nearer to the paddle wheel, and velocity is higher there than in Section IV. The results suggest that algal cells present in Section III were exposed to more sunlight and nutrients because of improved mixing, thus increasing their productivity.[3]

3.3 Power consumption

Power consumption was computed using Eq. (3) to further compare rectangular and round end models. The effects of the rectangular and round end models on power consumption with variations in *Re* are shown in Fig. 7. The results were computed at a paddle wheel rotational speed of 16. The hydraulic power is a function of flow rate. Thus, the power is high for the maximum *Re* and low for the minimum *Re*. More power was required for liquid circulation in Section I because power is dependent on flow rate. Mixing increased with increased water flow rate but also consumed more electrical power.[4]

The algal pond with a rectangular central wall end required more power than the round end model for water circulation in the channel and effective mixing of nutrients and CO_2 with algae cells. Power consumption for the rectangular end model increased significantly at the maximum *Re* because of a drastic increase in the velocity caused by its sharp edges. In the downstream channel, a vortex flow was produced by the sharp-edged rectangular end, which increased the velocity and power consumption. These results imply that the round end consumes less power and achieves a better mixing process. More hydraulic power is required for mixing the water vertically (Sections III and IV) to bring the algae cells from the bottom to the top surface of a pond for exposure to sunlight. Power consumption depends primarily on the average water velocity. Thus, Section III consumed more power than did Section IV because of higher water velocity.[4]

3.4 Cell damage

Microeddy length was computed using Eqs. (4) and (5) to estimate the effect of the central wall on algae cell membranes (Fig. 8). The effects of the rectangular and round ends on microeddy length were investigated using variations in the *Re* at a paddle wheel rotational speed of 16. Microeddy length depends on the turbulent energy dissipation rate, which was estimated using the PIV experimental average flow velocities in the pond. The length of the microeddy decreased with increasing *Re* and increased at the minimum *Re*. These findings show that microeddy length is inversely related to turbulent mixing, and higher mixing rates reduced eddy length, which may damage algae cells.[11,18]

Sections I and II are the most critical areas in the pond for the mixing of algae cells, thus the microeddy length must be estimated in these sections. Section II had greater microeddy lengths than Section I. The boundary of the algae cells near the end of the central wall (Section I) was at

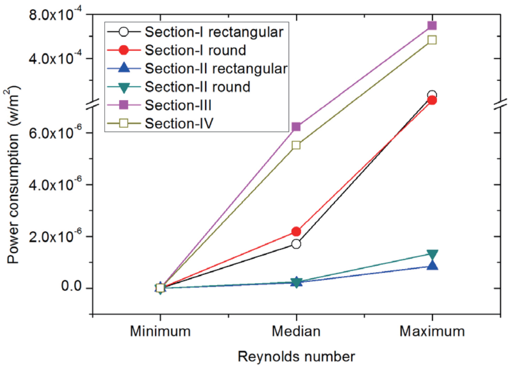


Fig. 7. (Color online) Effect of rectangular and round ends of the central wall on power consumption (W/m²).

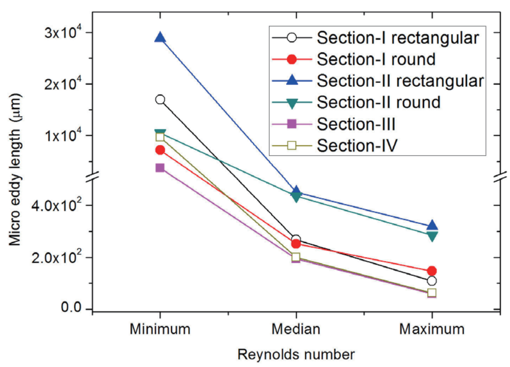


Fig. 8. (Color online) Effect of rectangular and round ends of the central wall on microeddy length (μm).

higher risk than in Section II because of the smaller microeddy length in the former. Therefore, the end design of the central wall must be optimized to reduce the risk of algae cell damage. The rectangular end model resulted in longer microeddies than the round end model. The microeddy length approached the value of the cell diameter (100 μm) in the rectangular end model at the maximum , whereas the central wall with round ends generated higher microeddy lengths than the cell diameter at all values. Hence, the round end model is more appropriate for algae cells because it caused the formation of longer microeddies. Section IV produced higher microeddy lengths because of low velocities. The microeddy length was reduced to below the cell dimension in Section III, which decreased algae productivity by destroying their cell membranes.[11]

4. Conclusions

The PIV technique was used to investigate the effects of central-wall-end design on the hydrodynamic properties of an algal pond. Two different shapes of central wall ends were compared (i.e., rectangular and round). Effects of the central wall ends design were examined using velocity field, *Re*, power consumption, and microeddy length.

Flow movement in the channel was reduced in the rectangular end model because of the formation of large recirculation zones and dead zones. The mixing process was higher in Section I because of the higher flow velocity in the upstream channel. Uniform vertical mixing was observed in Section III because of the higher water velocity produced by the paddle wheel. The round end model allowed algae cells to interact with nutrients and CO_2 better because of the more streamlined flow around its geometry. Power consumption was much higher in Section III because of the higher velocity. The round central wall increased the power for water circulation in the algal pond. A smaller microeddy length caused by higher turbulent mixing may damage the cell structure of algae cells. The microeddy length was reduced considerably in Section III, and the physical structure of algae cells in this area was vulnerable. The raceway pond with round central wall ends did not harm the cell structure and required less power for water circulation.

Acknowledgements

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References

1 L. Rodolfi, G. Chini Zittelli, N. Bassi, G. Padovani, N. Biondi, G. Bonini, and M. R. Tredici: Biotechnol. Bioeng. **102** (2009) 100.
2 B. Ketheesan and N. Nirmalakhandan: Appl. Energy **88** (2011) 3370.
3 H. Ali, T. A. Cheema, H.-S. Yoon, Y. Do, and C. W. Park: Biotechnol. Bioeng. **112** (2015) 297.
4 J. C. Weissman, R. P. Goebel, and J. R. Benemann: Biotechnol. Bioeng. **31** (1988) 336.
5 A. Richmond and H. Qiang: Appl. Biochem. Biotechnol. **63**–**65** (1997) 649.
6 A. Richmond and Q. Hu: Handbook of Microalgal Culture (John Wiley & Sons, Ltd., Oxford, 2013).
7 A. Richmond and J. U. Grobbelaar: Biomass **10** (1986) 253.
8 J. L. Mendoza, M. R. Granados, I. de Godos, F. G. Acién, E. Molina, C. Banks, and S. Heaven: Biomass Bioenergy **54** (2013) 267.
9 J. Cheng, Z. Yang, Q. Ye, J. Zhou, and K. Cen: Bioresour. Technol. **190** (2015) 29.
10 J. Huang, X. Qu, M. Wan, J. Ying, Y. Li, F. Zhu, J. Wang, G. Shen, J. Chen, and W. Li: Algal Res. **10** (2015) 64.
11 F. G. Camacho, A. C. Gómez, T. M. Sobczuk, and E. M. Grima: Process Biochem. **35** (2000) 1045.
12 J. Cornet, C. G. Dussap, and J.-B. Gros: Bioprocess Algae React. Technol. Apoptosis **59** (1998) 153.
13 J. Pruvost, J. F. Cornet, and J. Legrand: Chem. Eng. Sci. **63** (2008) 3679.
14 K. Liffman, D. A. Paterson, P. Liovic, and P. Bandopadhayay: Chem. Eng. Res. Des. **91** (2013) 221.
15 H. Hadiyanto, S. Elmore, T. Van Gerven, and A. Stankiewicz: Chem. Eng. J. **217** (2013) 231.
16 H. Ali, T. A. Cheema, and C. W. Park: J. Energy Eng. **141** (2014) 04014039.
17 R. Hreiz, B. Sialve, J. Morchain, R. Escudié, J.-P. Steyer, and P. Guiraud: Chem. Eng. J. **250** (2014) 230.
18 E. T. Papoutsakis: Trends Biotechnol. **9** (1991) 427.
19 X. Cao, J. Liu, N. Jiang, and Q. Chen: Energy Build. **69** (2014) 367.
20 Y. Fan, J. Wang, Z. Bai, J. Wang, and H. Wang: Sep. Purif. Technol. **149** (2015) 156.
21 J. Agunwamba: Water Res. **26** (1992) 1403.