Numerical Investigation on the Effect of Paddle Wheel Movement on the Flow Field Of High Rate Micro Algae Open Pond

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Abstract

Algae biofuels have received attention lately as they can provide a viable alternative to fossil fuels. Algal cells are continuously mixed by a paddle-wheel movement in a large pond, to prevent the settling of algal biomass and increase the productivity. Therefore the fuel cost is directly proportional to the paddle-wheel energy consumption. The three-dimensional simulation is done to investigate the effect of paddle-wheel rotation on the flow field and dead-zone regions of pond. The results are compared with the case of single phase flow with equivalent momentum source term, which has been used by other researcher in order to optimize pond geometry and estimates the power consumption of paddle-wheel. We observe different flow characteristics in comparison of two cases. When using a source term instead of paddlewheel, the dead zone regions of the pond and flow separation at the hairpin bends are overestimated as a flow depth variation due to centrifugal forces cannot be taken in to account also the depth increase is observed after the paddlewheel, which change the velocity field in entire pond and cannot be modeled by a single phase flow with the source therm.

Key words: Algae fuel, Pond, Paddle wheel, Multiphase simulation, Sliding mesh

Introduction

Algae organisms grow rapidly by consuming almost twice their weight in carbon dioxide (Moss et al.,1973). Biodiesel produced from algae due to its high oil yield, can be used as an alternative for replacing petro-diesel completely (Chisti et al.,2011). Although, the biodiesel production from algae is limited to small scales, industrial scale of algae cultivation and biodiesel production appear likely in the near future (Lundquist et al.,2010). Several fuels including hydrogen, methane, biodiesel/oil and ethanol can be derived from microalgae (Serrano et al.,2012). The produced algae also can be used as nutraceuticals, food additives or nutritional supplements (Richmond, 2008).

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A uniform mixing is necessary for the distribution of sunlight, carbon dioxide, and nutrients for the large-scale raceway ponds to prevent sedimentation of algae cells, to enhance the use of incident light exposure and receives a good supply of nutrients (Kumar et al., 2011). In open ponds, study the mixing of the algae culture is important in terms of input energy consumption and productivity (Hadiyanto et al.,2013). The algae pond is a closed loop channel which paddlewheels is used to circulate water through the pond.

Although there are a few numerical studies dealing with hydrodynamics of flow field in the pond (Liffman et al.,2013) the effect of paddlewheel circulation on a flow field is yet unknown. Due to complexity of multiphase flow modeling, grid generation conflicts caused by high length to depth ratio of ponds and considering the movements of paddlewheel, the pervious investigations, try to model the paddlewheel as a momentum source of flow and some of them uses the two dimensional calculations. In the present research we investigate the effect of paddlewheel movement and flow depth variation on the flow field of large scale pond. We also compare the results with the case which paddlewheel effect is considered as a momentum source.

Material and Methods

The simulation is conducted on high rate algae pond with length to wide ratio equal to 10 and the water depth of h=25 cm with the total volume of water in the pound is about V=1500 m^3. Two different methods are used to simulate the water circulation in the pond and obtain the flow field.

In the first method, simple steady, single phase simulation is used to simulate the water circulation in a pond. The paddle rotation is not taken in to account and it is represented by the momentum source which gives the equivalent velocity of 0.15 m/s to the circulating flow in the pond. This velocity is equal to average velocity obtained in a case which paddle-wheel is used to circulate the flow. In order to model the free surface of water, the slip boundary condition is applied to upper surface and the non-slip boundary condition is set to the channel walls. The pressure outlet condition is applied to the top of channel which is open to atmosphere.

The second simulation deals with the more complicated flow. The transient Volume of fluid (VOF) method is used in order to model the free surface and the flow depth variation. The rotational movement of paddlewheel is taken into account by applying of dynamic-sliding mesh approach. We assume that the fluid is initially at the rest and the paddlewheel rotation of 12rpm gives the momentum to fluid. The flow rate variation with the time is monitored.it observed that the flow rate reaches the repetitive pattern after about 290 second, which shows the required time to reach the quasi steady state solution. In order to couple the flow field between rotating and stationary mesh domain. The OpenFOAM, open source CFD software package with the interDyMFoam solver, which is capable of solving unsteady multiphase flow with considering rotational movement of the mesh domain around a paddle-wheel, is used to solve the equation of fluid motion. The Arbitrary Mesh Interface (AMI) is used as the boundary condition which projects the interface patches of domains and interpolates the fluxes. In both models the Re-Normalized Group (RNG) k–ε turbulence model is used to model the turbulence characteristics of flow field. The standard logarithmic wall function is applied to wall boundaries in each model. The turbulence intensity at the inlet is calculated as $I=0.16Re^{-0.128}$ and the turbulence length scale is equal to $0.07D_h$ where D_h denotes the hydraulic diameter of the channel.

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Results and discussion

The slight free surface variation is observed when modeling a two phase flow with considering a paddle-wheel movement (Fig 1). the free surface level increased just after the paddle-wheel and also surface waves is observed due to paddle-wheel water interactions. The dead zone is defined as place which its velocity is lower than 0.1 m/s which is lowest velocity needed to avoid settling of algae cells. The different flow field is observed when placing the paddle-wheel instead of momentum source. As it is obvious in Figure 2 the volume of dead-zone is highly decreases in a case of paddle-wheel driven flow. When the momentum source is placed instead of paddlewheel, it overestimates the separation at the inner area of channel bends (Fig 3) and underestimates the velocity at outer region of bends as can be seen in figure 4. This is because of flow depth cannot be varied in a single phase flow modeling and in fact the centrifugal force push the fluid into outer diameter of the bend and change the secondary flow regime at the hairpin bends. The centrifugal force causes the lateral slope in a water depth. Due to the slope of water level, pressure gradient is formed which causes the secondary flow and shifting the maximum velocity location. Figure 5 shows the velocity variation with the longitude distance which is non-dimensionalzed by channel wide (w_c) As seen in figure 5 the velocity variation after the paddle-wheel is not uniform as observed in the case of momentum source. The paddle wheel movement causes water depth rise just after a paddle so the static pressure will rise (Fig 6) and due to continuity of flow field the velocity magnitude decreases. As we distances from the paddle-wheel the water depth decreases and because of pressure gradients, the water hydrostatic pressure, converts into the fluid kinetic energy and it causes the fluid velocity to be increased and thus the water depth decreases. Comparing the velocity profiles of two cases after the paddle-wheel shows the same trend with plug like shape with slight difference in a shape (Fig 7). The velocity profile in vertical direction is compared in the middle of other side of channel which momentum source term and paddle movement does not have significant effect on flow field. as seen in case of momentum source the maximum velocity occur on the free surface but in a case of two-phase flow modeling due to shear layer between water and the air, the maximum velocity occur near free surface and is slightly lower it (Fig 8). The power of paddlewheel or a single phase flow is derived from flow rate (Q) and the pressure difference between the paddlewheel inlet and outlet

$$\text{Power} = \frac{\Delta P \cdot Q}{\eta_p}$$

Where η_p is the paddlewheel system efficiency. For a two phase flow the torque induced on the paddlewheel (T) can be obtained from the numerical solution and power easily calculated from the following equation

$$\text{Power} = 2\pi \cdot \frac{rpm}{60} \cdot T$$

In the case of paddle-wheel movement the average power is equal to 385.9 when it reaches a quasi-steady solution. When using a source term instead of paddle-wheel in a single phase flow with considering paddle wheel efficiency of 40% the calculated power is equal to 122.5 which is 1/3 of first case. This happen due to the turbulence generated around a paddle-wheel.

Conclusion

The effect of paddle-wheel movement and free surface of algal pond is investigated by comparing a two-phase flow simulation with considering a paddle-wheel movement to simple single phase flow and considering a paddle-wheel as a

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momentum source of flow. it is observes that the paddle-wheel movement causes the increase in free surface level of water after a paddle-wheel and thus due to continuity, the flow velocity is decreased after a paddle-wheel. Also it is shown that by using a momentum source instead of paddle-wheel movement the flow separation near hairpin bends are over estimated and the volume of dead zone is increased. Because single phase simulation is unable to predict the depth change due to centrifugal forces at the channel bends. Also the location which the maximum velocity occurs is slightly below the free surface in the case of two-phase flow; caused by a shear stress between the phases.

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Figures

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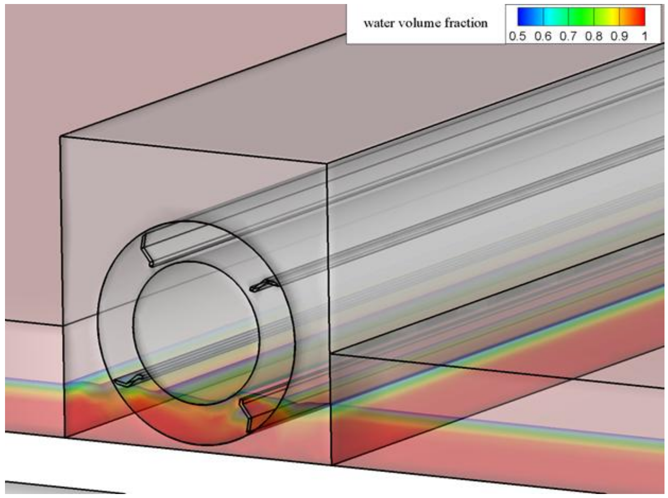

figure 1:Water volume fraction above 0.5 around a paddle-wheel

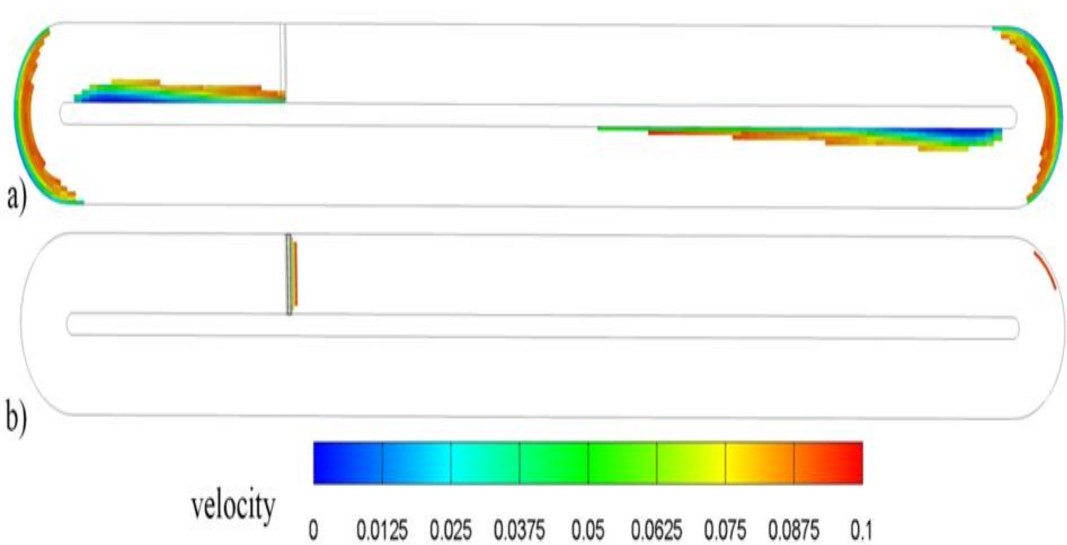

Figure 2: Iso-volume of velocity below 0.1 m/s which shows the dead zone region of the pond (a) with momentum source term (b) with paddle-wheel movement

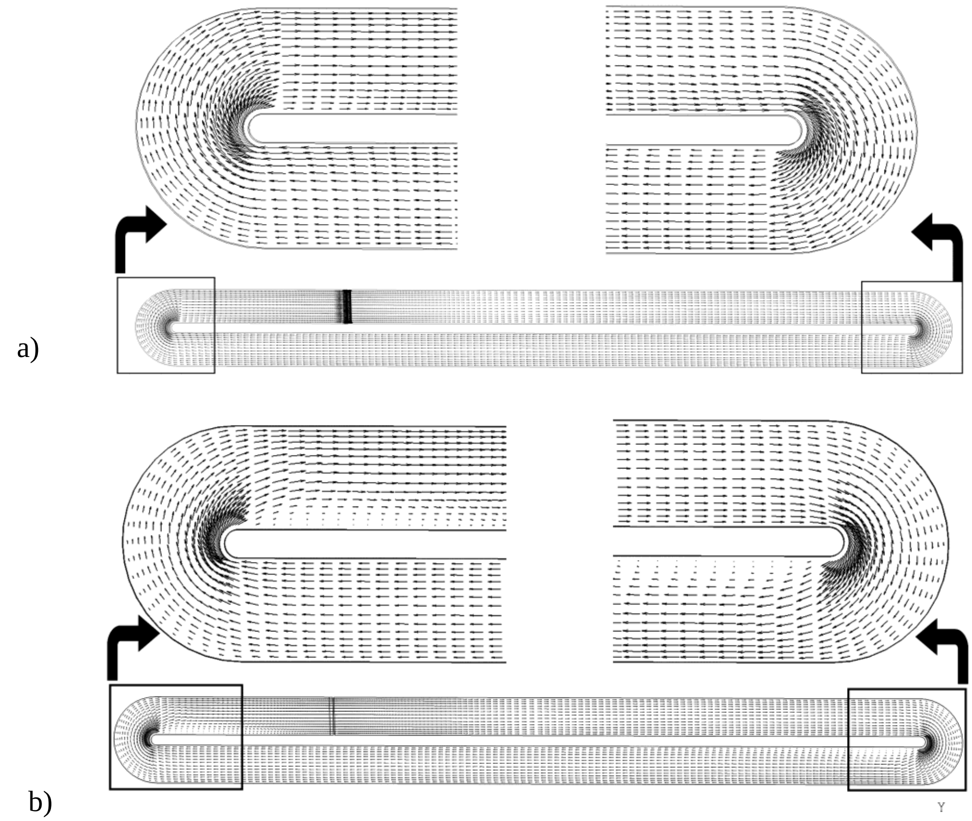

Figure 3: Velocity vectors on the surface of h/2. (a) With momentum source term (b) With paddle-wheel movement

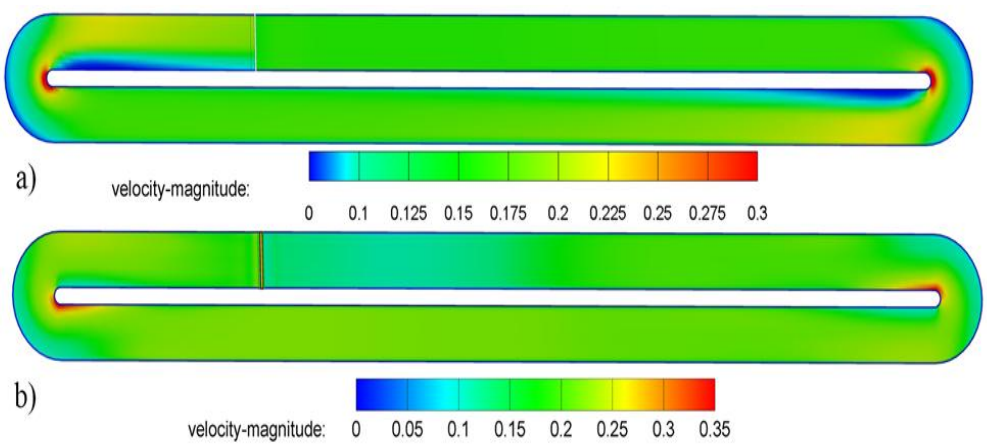

Figure 4 :Velocity contours on the surface of h/2. (a) With momentum source term (b) With paddle-wheel movement

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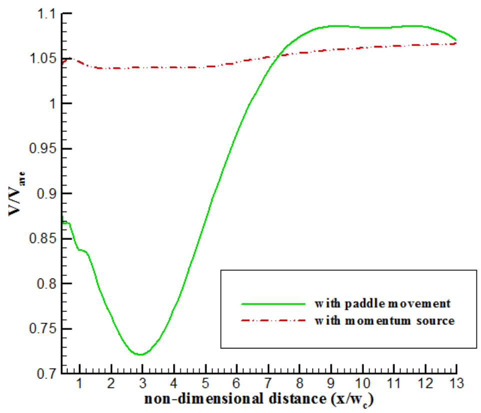

Figure 5 :Velocity magnitude 10 meter after the paddle wheel location on line located at center of channel on h/2, versus non dimensional distance

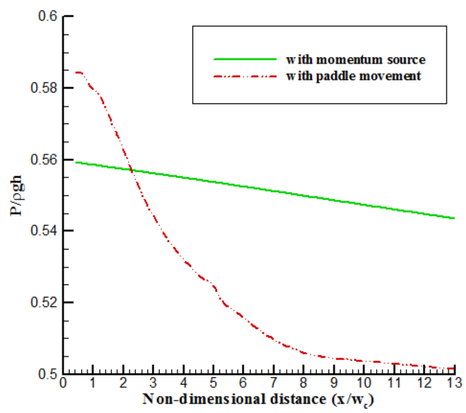

Figure 6 :Static pressure 10 meter after the paddle wheel location on line located at center of channel on h/2, versus non dimensional distance

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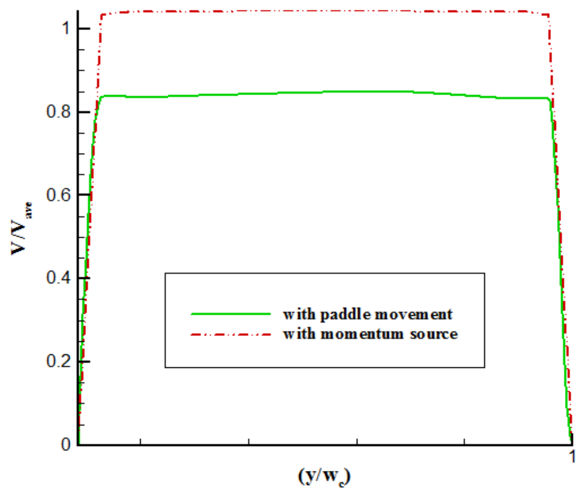

Figure 7:Velocity profile on x=10 and z=h/2

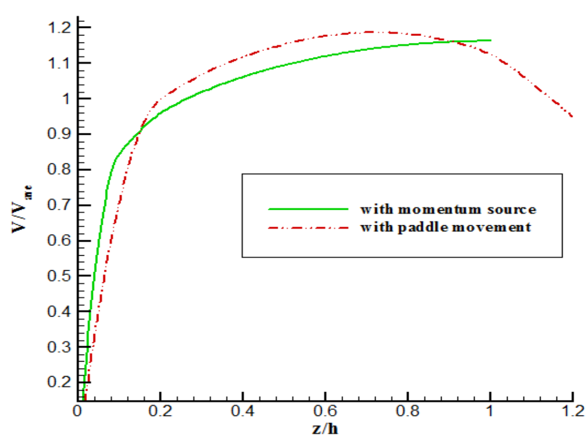

Figure 8:Velocity profile on vertical direction

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