International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 510

Numerical investigation and parameter optimization of an algae pond with serpentine path

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ABSTRACT

Raceway ponds with paddlewheels are widely used in mass algae cultivation. Algae sedimentation in the long straight part of the pond is a challenge due to poor vertical mixing of water flow in this section. In order to enhance vertical mixing, a novel algae pond with serpentine path was proposed previously as an alternative design to the paddlewheel raceways. However, the water mixing characteristics in the novel pond have not been thoroughly investigated and need to be quantitatively evaluated. Moreover, the important key design parameters including the dam number, dam length, and baffles should be optimized to enhance vertical water mixing and reduce dead zone area. The present study developed a 3D numerical model of water flow in the pond and studied the effects of dam number and dam length on the dead zone area, retention time and light/dark cycles.

Keywords: Algae pond; mixing; dead zone area; retention time; light/dark cycle; biofuel.

1. INTRODUCTION

Mass algae cultivation has attracted attention since algae is a promising feedstock for large-scale biofuel production [1,2]. Large scale algae culture systems are generally classified as open systems and closed systems. Raceway ponds are the most widely used open systems for commercial algae cultivation due to their ease construction and operation [3]. Paddlewheels are usually integrated with raceway ponds to circulate water and strengthen flow turbulence through disturbance induced by the wheels [4]. However, water mixing in the vertical direction is generally rather poor, particularly in the long straight part of the ponds and hence algae sedimentation is at high risk [5].Waller et al. [6] proposed an innovative Algae Raceway Integrated Design (ARID) pond, which employs a serpentine path in which water is driven by gravity. Xu et al. [7] further modified the ARID pond by combining the serpentine path with cascade flow to enhance flow mixing.

Mixing is critical for algae cultivation to prevent sedimentation and extended periods of dark respiration, and promote homogeneous distribution of nutrients, pH and photo-synthetically generated O_2 [8]. Vertical mixing is particularly important because it determines the frequency of algae cells travelling from the dark zone (bottom) to the light zone (water surface) of the pond [9], and light is one of the most critical factors that affect the algae growth rate [10]. In the literature, the Reynolds number (Re) is usually employed to define the mixing intensity of water flow in algae ponds [11]; however, it is worth noting that mixing is different with turbulence. Particularly strong vertical mixing can be induced by vortexes at low Re [12].

Many studies have been conducted to reduce the dead zone area and improve vertical mixing in raceway ponds, mainly focusing on the modification of pond design. Hadiyanto et al. [13] employed CFD to visually investigate the hydrodynamic characteristics of a typical raceway pond, and evaluated the effects of flow velocity, pond length to width ratio, and depth of culture on power consumption, dead zone volume and shear stress. Sompech et al. [14] studied the flow field in a raceway pond with deflectors, and reported the dead zone area can be significantly reduced. Chen et al.

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

[15] numerically investigated the effect of deflector installation and found that the ratio of light time in a light/dark cycle can be greatly increased with deflectors. Besides deflectors, efforts have also been made to increase vertical mixing and the light/dark cycle frequency by introducing baffles in the raceway pond; however, it is difficult to produce significant swirl flow with ordinary baffles since the water depth is generally shallow. Hence, special baffles are needed to enhance vertical mixing.

In the case of ARID ponds, Xu et al. [7] modified the first version of the ARID pond by adding several laterally-laid dams to form serpentine flow path, which significantly increased the retention time of algae in the pond. The dam height was controlled so that water can spill over the dam and mix with the main stream to create tumbling (up and down) flow, which was expected to strengthen vertical mixing. Xu et al. [16] further evaluated the flow mixing performance using statistics of temporal and spatial distribution of fluid particles. The pathlines of fluid particles were analyzed with regard to the number of light/dark cycle and the time retention that each particle staying in the light zone. Slots were also added in the dams near the pond wall to improve flow mixing in the dead zones.

The key design parameters such as dam number and dam length in the ARID pond have yet to be optimized. From the literature review, it can be concluded that quantitatively evaluating effects of the key design parameters on hydrodynamics of water flow in the pond is critical. Therefore, the flow field in a table-size ARID pond was numerically investigated in the present study with a focus on the dead zone area, residence time of the algae culture in the light zone and light/dark cycles. The dam number and dam length of the studied ARID pond were optimized.

2. METHODOLOGY

2.1 Model description and CFD setting

A schematic of the ARID pond model is illustrated in Fig. 1. The characteristic parameters of the ARID pond model are identical to the model reported in the Ref. [16]. Although the pond model is small compared to a real pond, the results obtained based on the model are still useful for design of a real pond because the dimensions are scaling down of a real pond by keeping the same Re. The length and width of the pond model are 1400 and 70 mm, respectively. It has a slope of 1:100 in order to enhance the spill flow over dams. Height of the pond wall and dam are 120 and 36 mm, respectively. Thickness of each dam is 25 mm. The distance between two adjacent dams is 220 mm. The inlet and outlet areas are both 1000 mm^2, and the water inlet velocity is 0.6 m/s. Average depth of the steady state water field is 41 mm.

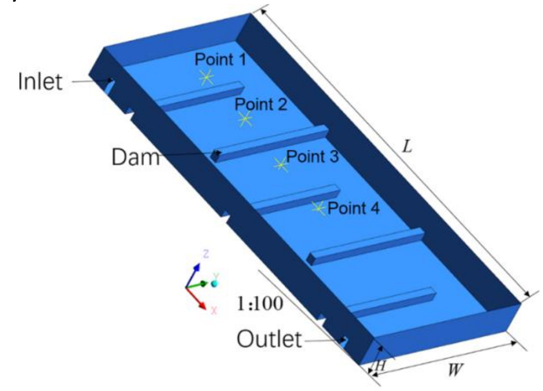


Fig 1 Schematic of the pond with serpentine path

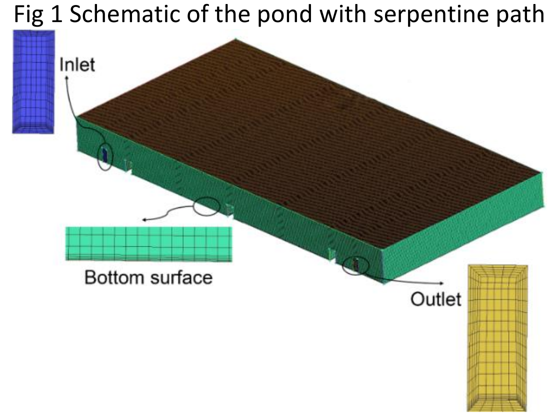


Fig 2 Grid meshing of the pond model

The 3D pond model was created in Creo and then imported into ICEM for grid meshing. Schematic of the model meshing is shown in Fig. 2. The hexahedral mesh was applied to the pond model and the grid meshing was refined in the inlet, outlet and the bottom surface. Velocity-inlet and pressure-outlet were set as boundary conditions. Time step of 0.005 s was used for transient flow calculation. The max iterations per time step was 45. The main governing equations were the Navier-Stokes equations. The turbulent flow was simulated by using the standard *k-ω* model, and the VOF model was applied to calculate the free surface between the liquid phase (water) and the gas phase (air).The standard *k-ω* model is selected because it is more suitable for the case with large number of vortices in the flow [6]. The turbulent intensity at the inlet was calculated as 4.73%. Although the flow characteristics with high algae concentration are expected to be different than that of water flow, numerical simulation of the algae flow is extremely complex; therefore, researchers usually assume the movement of algae cells follows the water flow and only investigate the hydrodynamics of water flow [5,13].

2.2 *Water level, grid sensitivity and model validation*

The water level becomes relatively stable when the mass flow rate in the outlet equals that in the inlet. Fig. 3 shows variation of mass flow rate at the outlet with time. At t=150 s, the mass flow rate in the outlet is 95% of the inlet. Therefore, the hydrodynamic characteristics of flow in the ARID pond were all investigated after t=150 s.

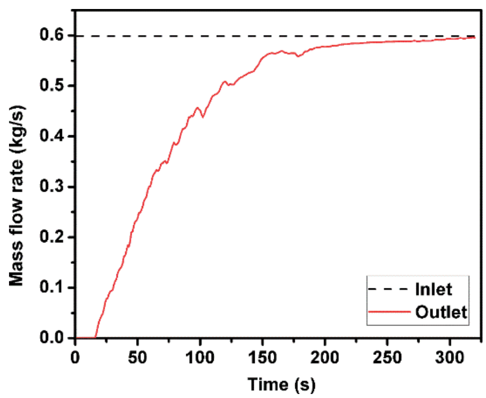


Fig 3 Variation of the mass flow rate in the outlet

Four different grid numbers, 0.5, 1.0, 1.6 and 2.1 million, were examined in a grid sensitivity study. Fig. 4 shows the calculated velocities based on different grid numbers at four independent points marked in Fig. 1. Heights in the *z*-axis are 40, 30, 20, and 10 mm for points 1 to 4, respectively. It can be seen that the calculated velocities at all points with 1.6 million grids agree well with those based on 2.1 million grids. The relative difference of velocities is within 3%. Hence, the following numerical investigations used a mesh with 1.6 million nodes.

The CFD model was validated by comparing the numerical results with the experimental data reported in Ref. [7] as shown in Fig. 5(b). Experimental study of the novel ARID pond model is very limited in the literature, and Ref. [7] is the only one which reported experimentally measured velocities. Again, it should be noted that the experiment was only for pure water without algae culture. Velocities were measured at five locations, which are marked as point *a* to *e* in Fig. 5(a). It can be seen that the numerical results generally agree well with the experimental data.

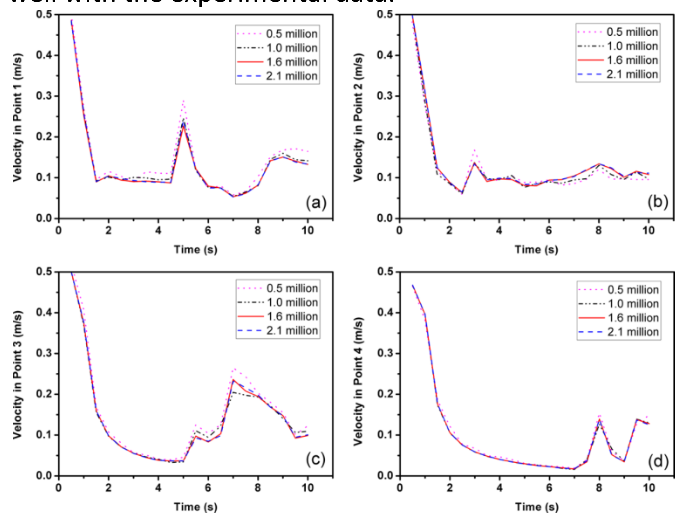


Fig 4 Grid sensitivity study for points 1 to 4 in the pond

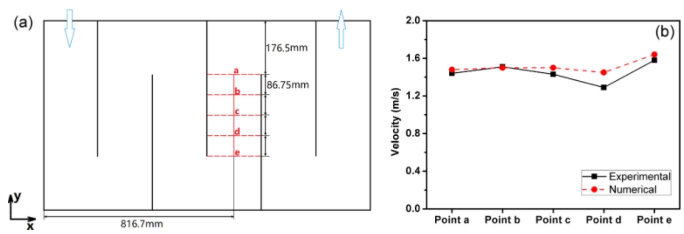


Fig 5 (a) Locations of the experimentally measured points, and (b) Numerical validation

2.3 *Quantitatively evaluated characteristics*

The hydrodynamic characteristics of the ARID pond

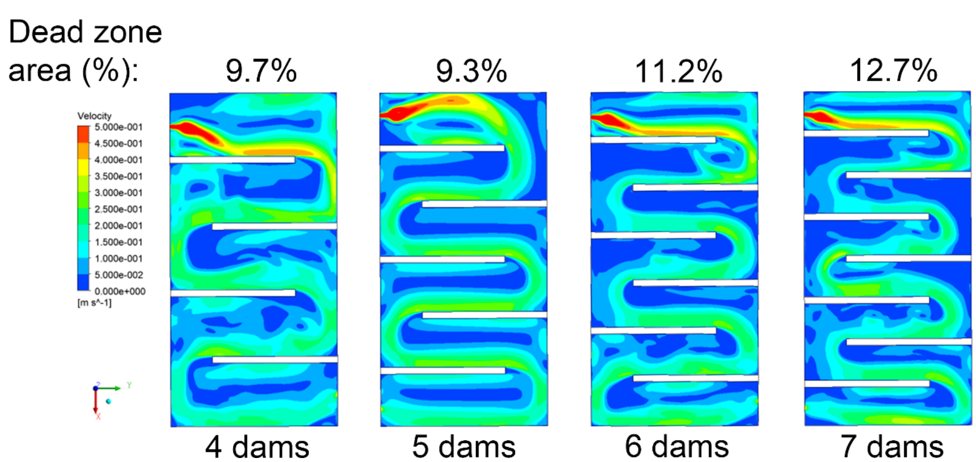


Fig 6 Velocity contour and dead zone area in the plane ofz = 18 mm

were quantitatively evaluated by the dead zone area proportion, retention time of algae cells in the light zone, and the light/dark cycle period. The dead zone is defined as the area at which the flow velocity is less than 2 cm/s according to general engineering experience. The dead zone area should be minimized since the algae are prone to sediment when the flow velocity is too low. The particle tracing method was employed to calculate the retention time of algae cells in the light zone and the numbers of light/dark cycles. A critical depth D_c was used to distinguish the light zone and dark zone. The frequency that cells pass through D_c defines the light/dark cycle time. In this study, Dc = 25 mm was used and the average retention time in the light zone and light/dark cycles of five particles were evaluated in the following sections.

2.4 Results and discussion

2.4.1 Effect of the dam number

Since total length of the ARID pond model is fixed, the dam number changes by varying the distance between adjacent dams. Different dam numbers ranging from 4 to 7 were numerically examined. The inlet and outlet are on the same side of the pond when the dam number is odd, and they are on opposite sides when the dam number is even.

Fig.6 shows the velocity contour and dead zone area in the pond model with different dam numbers in the plane of *z* = 18 mm. It is clearly that the main flow is significantly influenced by the number of dams. Areas with relatively low velocity are observed in the back of each dam and in the corners of the dam and the pond wall. The dead zone area proportion is 9.7%, 9.3%, 11.2% and 12.7% corresponding to the pond with 4-7 dams, respectively.

Fig. 7(a) shows the average retention time of algae cells in the light zone. After *t* = 150 s, the water level becomes relatively stable in the pond model. The retention times in the pond with 5 and 6 dams are higher than that in the pond with 4 and 7 dams, which is understandable because water needs to travel longer distance from the inlet to the outlet with more dams. When the total retention time is 60 s, the retention time in the light zone is 27 and 28.1 s corresponding to the pond with 5 and 6 dams, respectively. Fig. 7(b) indicates the average light/dark cycles in the same retention time. The light/dark cycles at the retention time of 60 s is 6.1, 7.3, 6.6 and 6.9 for the ponds with 4-7 dams, respectively. Therefore, the pond with 5 dams exhibits the best hydrodynamic characteristics for dead zone area and retention time as well as light/dark cycles. The dead zone area is less than 10%. About 45% of the total retention time is in the light zone, and the average period of one light/dark cycle is around 8 s averagely.

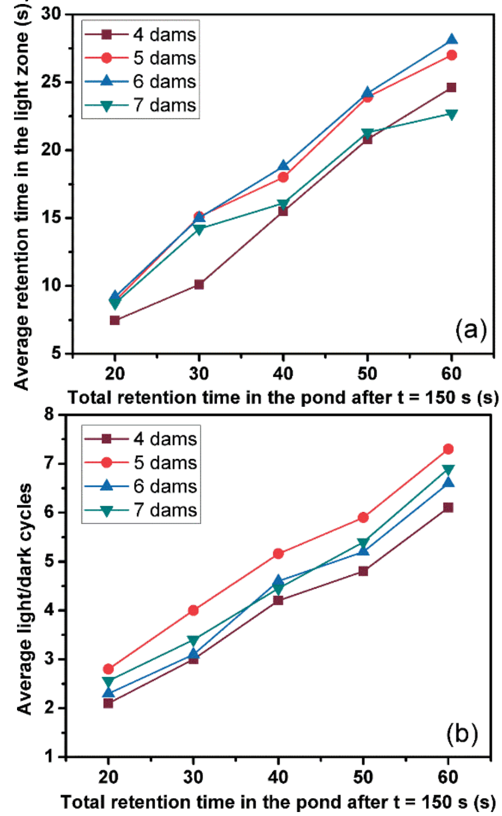


Fig 7 (a) Average retention time in the light zone, and (b) Average light/dark cycles at cases with different dam numbers

2.4.2 Effect of the dam length

The effect of the dam length on hydrodynamic characteristics of the pond was also investigated. Five different dam lengths of 0.60*W*, 0.68*W*, 0.75*W*, 0.81*W*, and 0.87*W* were examined, in which *W* = 700 mm is the pond width. Fig. 8 shows the velocity contour in theplane of *z* = 38 mm at ponds with different dam lengths labeled as case 1 to 5. The dam height is 36 mm, so this plane is slightly above the top surface of dams. Dead zone area is minimized and flow spilling over each dam is maximized in case 4 (dam length equals to 0.81*W*).

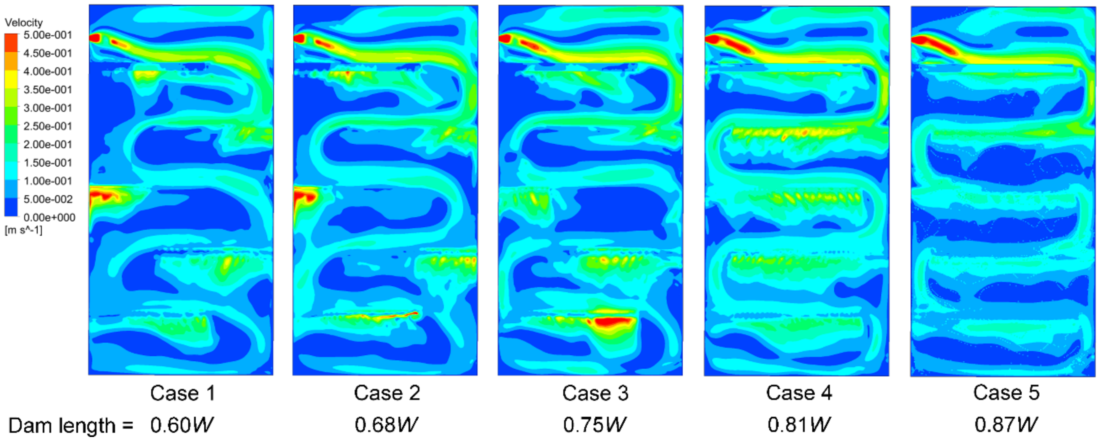


Fig 8 Velocity contour in the plane of z = 38 mm

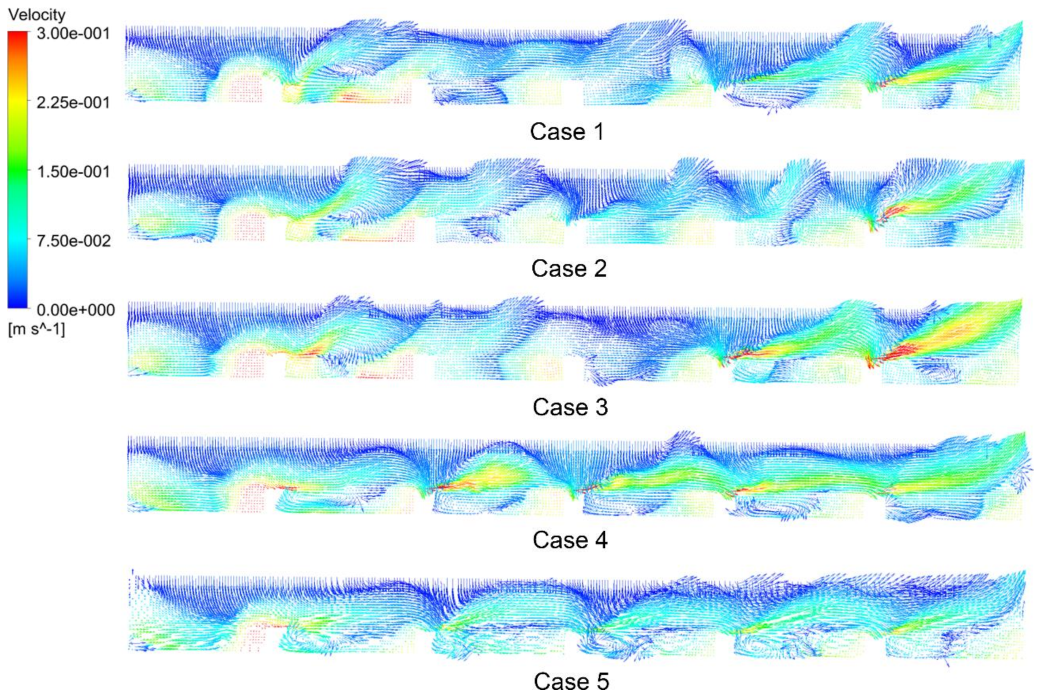
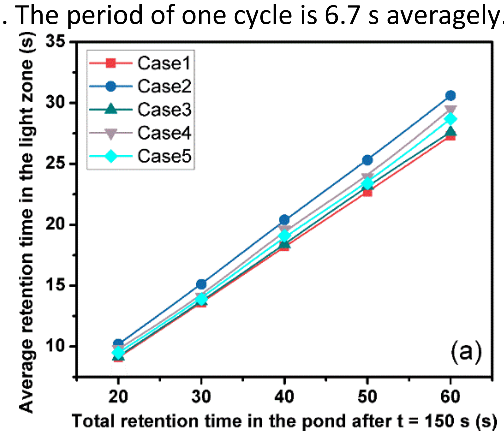


Fig 9 Velocity vector in theplane of y = 350 mm

Fig. 9 indicates velocity vector field in the plane of y = 350 mm at ponds with different dam lengths. It clearly shows that the air field in the top half area has velocity close to zero, and the water field in the bottom half area has velocity in the range of 0.1-0.3 m/s. Case 4 and 5 both demonstrate strong spilling flow over the dams and intense circulation are observed in the back of each dam. The circulation is favorable to enhance vertical mixing and unremittingly brings algae cells in the bottom to the surface of the pond.

Fig. 10(a) shows the average retention time in the light zone after t = 150 s. The results indicate that the dam length has less effect on the retention time compared to the dam number. When the total retention time in the pond is 60 s, the retention time in the light zone is in the range of 27.3 to 30.6 s. Case 2 and 4 have relatively longer retention time in the light zone. Fig. 10(b) shows the average light/dark cycles. Apparently case 4 has the highest cycle number of 8.9 compared to the other cases at the total retention time of 60 s. The period of one cycle is 6.7 s averagely.



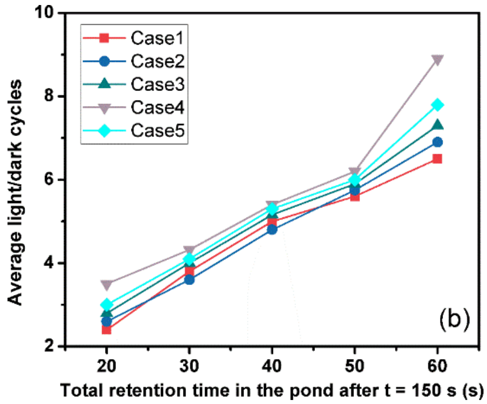


Fig 10 (a) Average retention time in the light zone, and (b) Average light/dark cycles at cases with different dam lengths

2.5 Conclusions

Effects of key parameters including the dam number and the dam length on important hydrodynamics of the novel pond with serpentine path were quantitatively evaluated with regard to the dead zone area, the retention time in the light zone and the light/dark cycles. Moreover, the influence of wing baffle installation was also investigated. It was concluded that the dam number of five and the ratio of dam length over pond length equal to 0.8 were the optimized pond design parameters. In such case, the dead zone area proportion in the plane of z = 1.8 cm is 8.5%. The retention time in the light zone is around 50% of the total retention time, and the average period of a light/dark cycle is about 6.7 s. The installation of baffles can significantly improve the hydrodynamic performance of the novel pond. The dead zone area proportion in the same plane is only 4.9% with baffles. The retention time in the light zone increases to 70% of the total retention time, and the period of a light/dark cycle is only 3.9 s.

ACKNOWLEDGEMENT

Support from Shenzhen Science and Technology Innovation Commission (JCYJ20200109113439837) is gratefully acknowledged.

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