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IN-SITU ALGAE CONTROL USING WATER-LIFTING AERATORS IN A EUTROPHICATED SOURCE WATER RESERVOIR

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Taking the eutrophicated Shibianyu Reservoir in Northwest China as a study case, the effect of in-situ algae control using water-lifting aerators was numerically investigated with Fluent. Two submerged water-lifting aerators with different circulation flow rates were installed with different local water depths respectively. Accurate geometry data required for the mesh generation were obtained using a global position system based on real time kinematic technique and a depth meter. The three-dimensional flow velocities were measured with an Acoustic Doppler Profiler. The temporal distribution of velocity at the domain inlet, the vertical distributions of initial water temperature and algae concentration, the density and viscosity with water temperature were all imposed with user defined functions written in C programming language. The algae transport was also simulated with Euler-Euler multiphase model and the turbulence was modeled with RNG model. Before running the aerators, the algae concentrations increased from 4.00 million cells.L^{-1} at the surface to 9.20 million cells.L^{-1} at the depth of 5m, decreased to 0.16 million cells.L^{-1} at the depth of 15m and then remained constant in the deeper water. At day 10 after operating the aerators, the water temperature became nearly uniform in the reservoir, the algae content in the surface area was greatly decreased, but the algae content in the lower water was increased. The dominant microcystis aeruginosa with a floating velocity of 0.000275m/s was transported to and deposited at zones near the bottom and side wall. The distributions of simulated flow velocity, water temperature and algae content agreed well with the measured ones on the field. Based on the simulation results of algae concentration under five water levels, five temperature gradients and three air flowrates, the times required for complete mixing of algae within the water depth of 5m were comprehensively evaluated and the optimized operational conditions were suggested for the reservoir management.
Keywords: Algae control; source water reservoir; water-lifting aeration; numerical modeling; process optimization

INTRODUCTION

Algae pollution is a threat to the quality and safety of drinking water worldwide[1-2]. High concentrations of algae in raw water would not only directly influence the safety of drinking water, but also increase the difficulty and cost of water purification in the water plant[3-4]. At present，the in-situ algae inhibition is mainly achieved by physical, chemical and biological methods[5-6], during which chemical removal would inevitably pollute the environment.

Microcystis aeruginosa is the dominant species of algae in most drinking water source reservoirs and it can float upward at a characteristic velocity of 0.000275m/s in the water[7]. In deep stratified reservoirs, the main method of in-situ algae control is destratification, which has been applied in countries such as Britain, Japan and Korea and has shown good algae control effects[8-10]. The water-lifting aerator is a newly-designed mixing and oxygenating device, an in-situ reservoir eutrophication inhibition technology with a broad application prospect[11-12]. The aerator consists of an aeration chamber, a reflux chamber, a gas chamber, central riser, air releasing device, watertight compartment, gas pipes and anchoring device. For detailed performance and technical requirements please refer to other document[11-12]. The mechanism of inhibiting algae growth by water-lifting aeration is achieved by circulated flow from top to bottom caused by rising air slug in the central riser[12], the algae are transported to the lower water layer and eventually die due to unfavorable growing conditions.

To illustrate the process of algae inhibition by water-lifting aeration in stratified reservoirs, based on the typical operational conditions of the water-lifting aeration system used to improve water quality of Shibianyu Reservoir in Xi'an, the fields of flow and algae concentration outside the water-lifting aerator were simulated with FLUENT[13-14] and validated against the field data. To further optimize the operational conditions of water-lifting aerators, the mixing of algae by water-lifting aeration under different water depths, temperature gradients and air flowrates were numerically simulated. The outcomes of this study are very helpful to understand the process of algae inhibition by water-lifting aeration and to determine the optimal time of operating water-lifting aerators in stratified reservoirs.

1. NUMERICAL SIMULATION METHODS AND CONDITIONS

1.1 Study site

Shibianyu reservoir is a medium canyon-shaped reservoir located in a warm temperate zone about 35km southwest of Xi'an city in Shaanxi province, northwest of China(Fig.1a). Shibianyu reservoir has a total capacity of 28.1 million m^3 and supply 30 million m^3 water to Xian every year. Generally, the high water level is 731m above sea level(a.s.l.) and the minmum water level is 675m a.s.l. As the city alternate water resource, Shibianyu reservoir water quality plays an important role on ensure urban water security.

During the period from July to October, enough illumination conditions, high water temperature and stable thermal stratification promoted the excessive growth of cyanobacteria. A large number of green flocs were observed to appear on the surface of reservoir (Fig.1b.), and the algae concentration could be up to 100 million cells.L^{-1} which Microcystis accounted for 92%. The algal bloom seriously affected the ecological balance of reservoir and threatened the drinking water safety of Xi'an City. To control the algal bloom and improve the water quality of Shibianyu Reservoir, two water-lifting aerators were installed near the dam of the reservoir. The 1# aerator was chose to the dam, where the water depth of this region was relatively shallow. The 2# Water-lifting Aerator was located in the deepest point of reservoir. In order to determine the effectiveness and optimized operational conditions of algae inhibition using the water-lifting aerators in Shibianyu reservoir, fields of flow and algae concentration were numerically simulated with Fluent and validated against the field data.

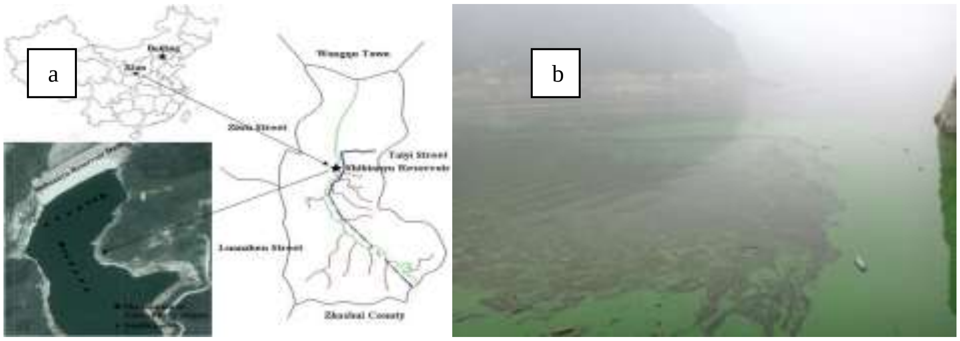

Fig.1. Illustration of Shibianyu reservoir.(a) Location of the water-lifting aerators and monitoring sites;(b) Photograph of reservoir surface during algal bloom.

1.2. Simulation methods

1.2.1 Simulated domains

The flow field outside an aerator was simulated with an axisymmetric model and only the right part of the water body was studied. The computational domains were simplified to have a radius of 300m and varying water depths dependent on the reservoir topography. The aerator was simplified to a cylinder with a radius of 0.375m and treated as a black body, its inner flow was not considered. The outlet of the aerator was considered as the inlet of the computational domain, and the inlet of the aerator was considered as the outlet of the flow domain. The outlet and inlet of the submerged aerator were 16m and 6m above the reservoir bottom. Figs. 2a-2b show the grids of domains outside two water-lifting aerators.

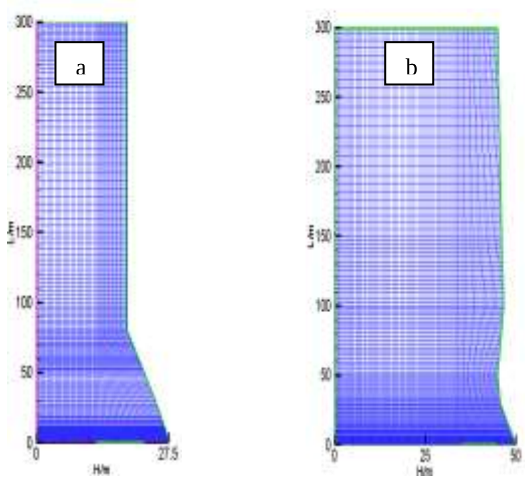

Fig.2 Computational grids for domains outside water-lifting aerators.(a)1# aerator;(b)2# aerator.

1.2.2 Simulation conditions

Flow field outside a water-lifting aerator is mainly influenced by hydrological and operational factors. Hence, the effectiveness of algae inhibition by water-lifting aeration was mainly simulated under different conditions of water depths, temperature gradients and inlet velocity periods as shown in Table 1.

Table 1 Simulation Conditions

Cases	Temperature gradients within water depth of 30m (℃/m)	Water depths (m)	Inlet velocity periods (s)
1	0.04	27.5/50	210/160
2	0.73	27.5,35,42.5,50,65	160
3	0.17,0.30,0.47,0.60,0.73	50	160
4	0.73	50	80,160,320

1.2.2 Boundary and initial conditions

Boundary conditions: Velocity-inlet was used to describe the water-inlet of the simulated region. Due to the intermittent release of air from the outlet of the aeration chamber, the flow velocity in the rising pipe varies periodically. A mathematical model has been established to describe the water velocity in the central riser with time during one development period of air slug[12], but the flow rate after the air slug is completed released out of the central riser cannot be obtained with the model. In order to obtain this, a VOF model for gas-liquid two-phase flow was adopted to simulate the actual flow with Fluent, and the actual velocity distributions were accurately achieved as shown in Fig. 3 and imposed as inlet velocity by user defined function (UDF) written in C programming language. The temperature of water-inlet of simulated region defined by a UDF was the average value of temperature of water-outlet of simulation region at the previous simulation time. Pressure-outlet was used to describe the water-outlet of the simulation region and the pressure was decided from the water depth.

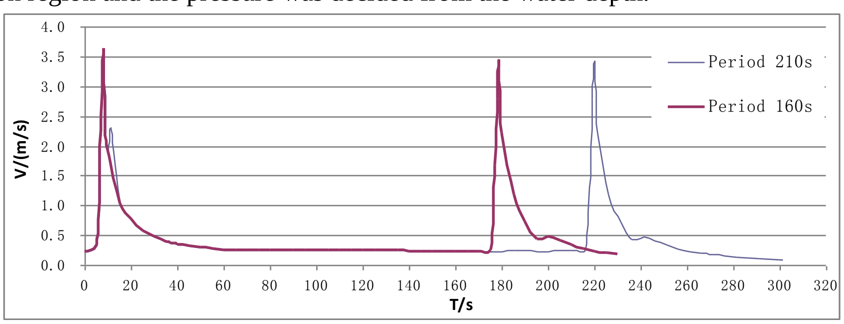

Fig. 3 Distributions of inlet velocity with time

Initial conditions: Based on the measured data of water temperature and algae concentration of Shibianyu Reservoir, the vertical distributions of water temperature and algae concentration were defined by UDF. The dependences of water density and viscosity and water temperature were defined by UDF before simulation.

1.2.3 Solving and data analyzing methods

Solving methods: Renormalization-group (RNG) κ-ε model, which was suitable for dealing with the problems at high strain rate and strong bending streamline, was used to be the turbulence model (κ and ε were turbulent kinetic and energy dissipation rate, respectively). Heat transfer of surface and subsurface water was considered[15], and heat transfer conditions were given by UDF. The first order upwind scheme was used to discretize the equations, PISO (pressure implicit splitting of operator) and pressure based implicit solver were applied to solve the unsteady equations.

Algae concentration was computed by Euler-Euler multi-phase model. According to preliminary results[7], typical diameter and floating rate of *Microcystis aeruginosa* here were 0.5 mm and 0.000275 m/s respectively. So if the downward velocity reached 0.000275 m/s, it is able to prevent the floating of *Microcystis aeruginosa* basically. Based on the force balance between the gravity and the floating force acting on the algae, typical density of *Microcystis aeruginosa* was first calculated by Stokes equation.

2. PROCESS OF ALGAE INHIBITION BY WATER-LIFTING AERATION

2.1 Validation of simulated flow velocity

Flow fields outside water-lifting aerators were measured by three-dimensional acoustic Doppler profilers (ADP, LAUREL company WH600kHz, USA). ADP measures the flow velocity with the principle of acoustic Doppler[16-17]. According to the simulated results, flow out the aerator was unsteady, and flow fields 50m away from the aerator was substantially independent of the periodic flow after running for a period of time.

ADP provided flow velocities based on the earth-based coordinate system. Because Global Positioning System (GPS) measuring instrument was not installed during the test, horizontal velocities measured by ADP could not be projected to the velocities of the simulation coordinate system. Therefore, vertical flow velocity independent of coordinate system was used for verification. Actually, the vertical velocity is critical to the transport of algae over the water depth. Compared with the data of vertical flow velocity derived from ADP as shown in Figs. 4a and 4c, the simulated vertical velocities as shown in Figs. 4b and 4d agreed well with the measured data.

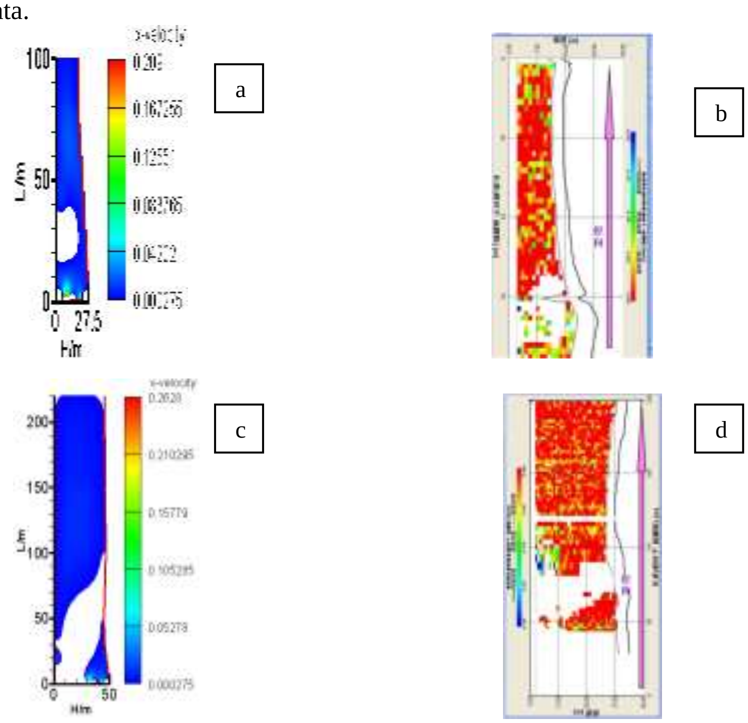

Fig. 4 Comparison of measured and simulated vertical velocity contours.(a)Simulated, 1# aerator; (b)Measured, 1# aerator; (c)Simulated, 2# aerator; (d)Measured, 2# aerator.

2.2 Process of algae inhibition

Theoretically, inert pollutant can be transported in the water by molecular diffusion, turbulent diffusion, advection and dispersion of shear flow. The density of an algal lump is similar to water density[7], the velocity outside the aerator was small, turbulent intensity was weak, so advection by circulated flow generated by water-lifting aeration was the main transport mechanism of algae in the reservoir. The circulated water flow due to mixing of water-lifting aeration transported lower-temperature water in the bottom to the surface, reducing water temperature in photic zone; large amounts of algae in photic zone were carried to the lower aphotic zone, weakening photosynthesis of algae. The algae concentration in the surface area was reduced gradually by the mixing together. As can be seen from Fig. 5, with the operation of aerators, water in the bottom area was mixed much slower than the upper area and water near aerators was mixed faster than water far from aerators.

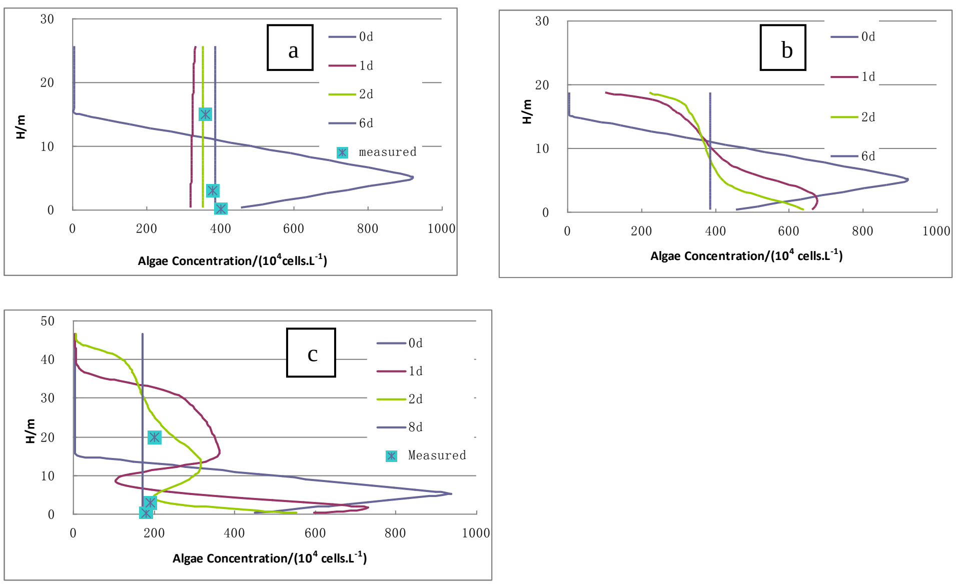

Fig. 5 Vertical distributions of algae concentration outside water-lifting aerators. (a)20m from 1# aerator; (b) 100m from 1# aerator; (c) 100m from 2# aerator.

For 1# water-lifting aerator, when it ran for 2 days and 6 days, algae in water 20m and 100m away from the aerator were almost completely mixed. Algae concentration in surface water was reduced significantly from the peak value of 9.2 million cells.L^{-1} to that about 4.00 million cells.L^{-1} after 6 days, while at the bottom it gradually increased from 0 to 4.00 million cells.L^{-1}. Compared with measured data, the predicted algae concentrations were relatively ideal, and the prediction error decreased gradually with prolonged running time. The prediction error of the algae concentration at the beginning of operation was larger mainly due to the unevenness of mixing caused by intermittent flow generated by water-lifting aeration. When the algae were substantially mixed in the vertical direction, the predicted and measured values were relatively close. For 2# water-lifting aerator, the mixing of algae was slower than that of 1# aerator due to the higher water depth.

3. OPTIMIZATION OF OPERATIONAL CONDITION OF AERATOR

With the running of water-lifting aerator, the algae concentration gradually reached a constant value over the water depth. When the algae were completely mixed in the reservoir, the algae inhibition was the strongest. Therefore, the time required for complete mixing of algae was used as a parameter to optimize the operational condition of water-lifting aerators. Under different water depths, temperature gradients and velocity periods, the variations of algae concentration within the water depth of 5m for different cases were analyzed from the simulated data, and the results were plotted in Fig. 6.

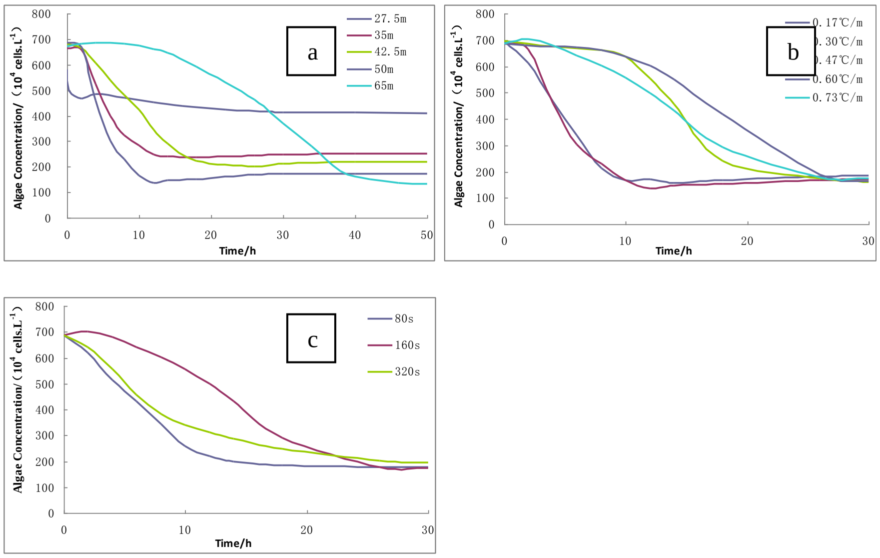

Fig. 6 Variations of average algae concentration within the water depth of 5m under different conditions.(a) Water depth; (b)Temperature gradient;(c)Inlet velocity period.

From Fig. 6, the time required for complete mixing of algae increased with the water depth, temperature gradient and inlet velocity period. The algae were mixed mainly by advection, which is closely related to the mixing of upper layer water and lower layer water. As the water depth and temperature gradient increased, buoyancy resistance acting on water flow became larger, hence the time required for complete mixing of water and algae would increase. As the inlet velocity period is negatively related to the air flowrate, larger period means lower air flowrate and smaller energy input to the water for mixing. So, the time required for complete mixing of algae increased with inlet velocity period. Using these data of time, the operational condition of water-lifting aerator can be determined.

4. CONCLUSIONS

(1)Simulated profiles of flow velocity and algae concentration outside water-lifting aerators agreed well with the measured data in Shibinayu Reservoir, China. The developed numerical simulation method using Euler-Euler model of Fluent can be applied to simulate the hydrodynamics and algae transport under different water-lifting aeration conditions in stratified reservoirs.

(2) Algae in the surface layer were transported to the lower layer mainly by advection and diffusion due to water-lifting aeration, where the algal growth was inhibited due to the unfavorable environments. The mixing of algae was faster in the upper area and in the area nearer to the water-lifting aerator. The mixing of algae became slower as the water depth increased.

(3)Influenced by the buoyancy resistance acting on water flow, the time required for complete mixing of algae increased with the water depth and temperature gradient, but decreased with the air flowrate. Using numerical simulation, the operational condition of water-lifting aerators can be determined based on the time required for complete mixing of algae.

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