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Structure optimization of CycloBio fluidized sand biofilters based on numerical simulation

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ABSTRACT

To improve the removal efficiency for dissolved wastes within CycloBio (CB) fluidized sand biofilters (FSBs) in recirculating aquaculture systems, we investigated their structural design and optimization using computational fluid dynamics (CFD) modeling tools, an orthogonal test method, and experimental verification. Results showed that the effects of structural parameters on bed expansion from large to small were: cone height, cone diameter and slot width. The best combination was: cone height 60 mm, cone diameter 165 mm, and slot width 1.0 mm. The solid phase was well distributed not only in the radial direction, but also in the axial direction in the optimized CB FSB. The bed expansion (40%–120%) was increased about 13%. Energy savings were 21%–28% at the same bed expansion. When the optimized CB FSB was used to treat synthetic aquaculture wastewater, with three bed expansions and four levels of C/N, total ammonia nitrogen removal rate expressed per unit of expanded bed volume was high, from 629 to 881 g m^{-3} day^{-1}. All results indicated that the structure of the optimized CB FSB was more reasonable and that the combination of CFD simulation and the orthogonal test method could be successfully applied to structural optimization.

1. Introduction

Increasing with the shortage of water resources, management of environmental pollution, and food safety, recirculating aquaculture is becoming more and more popular. Good water quality is the basis for successful recirculating aquaculture. Biofiltration is critical to wastewater treatment in recirculating aquaculture systems (RAS) because the selection of biofilters influences the capital and operating costs of systems and the consistency of effective water treatment (Summerfelt, 2006). There are many kinds of biofilters that are commonly used in RAS, including submerged biofilters, trickling biofilters, rotating biological contactors, floating bead biofilters, dynamic bead biofilters and fluidized beds biofilters (Timmons et al., 2002).

Compared with other types of biofilters, fluidized beds are relatively advanced and are used in many areas, for example, remediation of groundwater (Kenari and Barbeau, 2014), and many uses in the chemical industry (Guan et al., 2014). In recirculating aquaculture, fluidized sand biofilters (FSBs) have been widely used in North America (Summerfelt, 2006). As the media in FSBs is inexpensive and its specific surface area is larger, there are many advantages of FSBs, including high efficiency of water treatment (TAN removal of 50–90%), small size, low cost, and no need of backwash.

Conventional FSBs include five types of flow distribution mechanisms (Summerfelt, 2006); CycloBio fluidized sand bed (CB FSB) is the only type not utilizing a manifold at its top (rotational flow distribution mechanism), whereas the other types do. The CB FSB operates with relatively little headloss across the flow inlet slot than that across the orifices of horizontal pipe manifold flow distribution mechanisms (Summerfelt, 2006). Although no floor abrasion has been observed, bottom protection is best to be made. And vacuum breaker is necessary to enhance security of system. Hence, CB FSBs are commonly used in RAS. However, existing studies about CB FSBs were not systematic. Summerfelt (2006) introduced the mechanism of CB FSBs and the sand selection criteria. Davidson et al. (2008) investigated the efficiency of CB FSBs in wastewater treatment and operation management. Few studies addressed the design of CB FSBs and mostly adopted experimental and theoretical methods. Simulation is a new method which involves low cost, short experiment time, and reduces workload (Sun, 2011;

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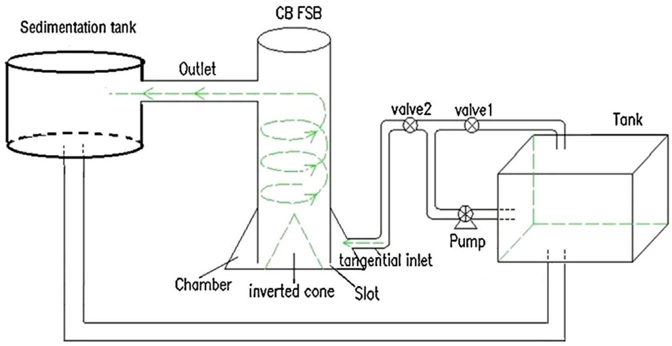

Fig. 1. Schematic diagram of the recirculating system to treat synthetic aquaculture wastewater.

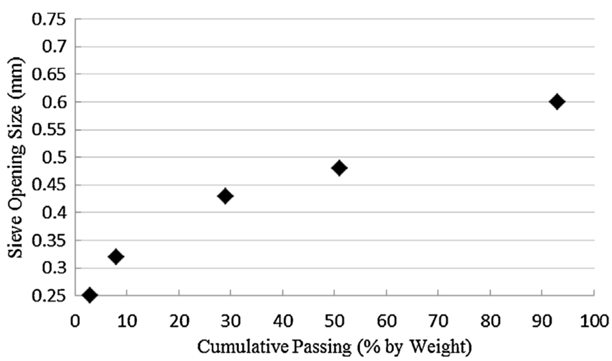

Fig. 2. Sieve analysis of silica sand in CB FSB (uniformity coefficient, UC = D_{60}: D_{10} = 1.44).

Zhou et al., 2011). Therefore, we studied the design and optimization of CB FSBs with the combination of numerical simulation and experiment validation. We had two aims: (1) improving the efficiency of CB FSBs in wastewater treatment; and (2) minimizing the cost of research.

2. Material and methods

2.1. Experimental set-up

A schematic diagram of the recirculating system used to treat synthetic aquaculture wastewater is presented in Fig. 1. Synthetic aquaculture wastewater was pumped from the tank to the CB FSB through the main pipeline, while the bypass was used to control the inflow of CB FSB. Water was injected tangentially into an annular space. This continuous water flowing through the annular space created strong water rotation. The water then entered the FSB vessel through a slot at the base of the bed and around the circumference of the vessel. An inverted cone, incorporated into the center of the floor of the vessel, was used to rotate the upward-flowing water, which improved the bed expansion.[1] At low superficial velocity, the quartz silica sand (sieve analysis shown in Fig. 2) remained stationary at the base of the vessel, and water flowed upward through pores without moving the sand. However, at higher superficial velocity, especially when the drag forces exceeded the down gravity forces on the sand grains, the particles were lifted and fluidization occurred. The dissolved waste in the water was absorbed and transformed by microbes attached to the surface of sand. Effluent from the CB FSB flowed into the sedimentation tank and then recirculated to the tank.

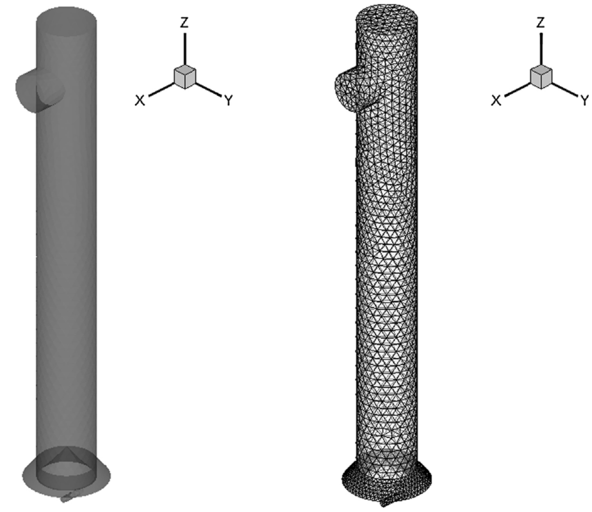

Fig. 3. Model and mesh of CB FSB.

2.2. Orthogonal test

The treatment of wastewater in the CB FSB was determined by the comprehensive impact of structural parameters, operating parameters, and evaluation indexes. In this study, at the same operating conditions and with bed expansion as the key evaluation index, the effects of different structural parameters on evaluation indices were investigated. The structural parameters evaluated were: cone height, cone diameter, slot width, bed diameter, as well as inlet pipe diameter and its cutting-in angle, among others. The first three parameters were selected as the primary factors. To get a comprehensive result and reduce test times, orthogonal experiment design (Wang, 2004) is a scientific method for multi-factor and multi-level. Factors are in the row and levels are in the line, especially part of all tests is selected according to orthogonal table. In this table: different numbers are in the same frequency in every line; different ordered pairs in the same row are in the same frequency in any two lines, too. Hence these selected tests are uniformly distributed and representative. In the optimization of CB FSB, effects of all factors and levels were examined using an orthogonal table $L_9(3^4)$, and the experimental design is shown in Table 1. And the other dimensions of CB FSB are shown in Table 2.

2.3. Numerical simulation

2.3.1. Modeling and mesh generation

A 3D substance geometry model was built using CFD software FLUENT 6.3 (Fig. 3). The model was divided into several areas, and the mesh in the greater change in flow field area was encrypted. The model was meshed to 500,000–900,000 grids by a tetrahedral-structured meshing technology.

2.3.2. Boundary conditions and solution algorithm

The reliability of simulation results depended on the rationality of boundary conditions in simulation. The movement of fluid changed with time, so unsteady flow was set in the simulation. The wall function was used near the wall, and no-slip velocity boundary conditions were chosen. The Eulerian model was selected as the multiphase flow model, the RNG k-ε model was selected as the turbulence model, the Syamlal–O'Brien correlation was selected to define granular kinetic viscosity, and Gidaspow

[1] When a sand bed is expanded, its total height is some percentage greater than its initial static height. Percent bed expansion is calculated by subtracting the expanded bed height from the static bed height, dividing this difference by the static bed height, and then multiplying by 100 (Summerfelt, 2006).