FLUENT Simulation Design and Optimization of Biological Aerated Filter

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Abstract. In this paper, a small biological aerated filter for experimental use was designed, and a method was explored to optimize the nitrogen removal efficiency by using FLUENT software to simulate the particle size of the filler, the amount of the filler, the initial concentration of ammonia nitrogen, dissolved oxygen and other operating parameters. Through the simulation experiment, the optimal design parameters of the particle size of filler, the amount of filler, the initial concentration of ammonia nitrogen and the dissolved oxygen of the biological aerated filter are 4mm, 60%, 15% and 1.5%, respectively, when the removal efficiency of ammonia nitrogen exceeds 30% reported in the literature. It provides a reference for the experimental research and practical application of biological aerated filter (BAF) denitrification.

Keywords. BAF; FLUENT simulation; Nitrogen removal; Optimized design.

1. Introduction
As a representative process of the third generation of biofilm, biological aerated filter (BAF) has the advantages of compact structure, convenient operation and high treatment efficiency, and has been widely used in municipal and industrial wastewater [1-2]. However, the biological aerated filter is often exposed to the disadvantage of low nitrogen removal efficiency in practical application. The study of Zhang Ruijing et al. [3] showed that the nitrogen removal efficiency of a biological aerated filter in a sewage treatment plant was 58.11%, while the ammonia nitrogen removal efficiency of Yue Zhifang et al. [4] was only 37.5%. And in the design and calculation of biological aerated filter is often used in the empirical or semi-empirical formula, these formulas lack of rigorous theoretical basis, resulting in the formula varies from person to person and various, so in the actual design selection and calculation of the work is large, and it is difficult to ensure accuracy. It is urgent to improve the nitrogen removal efficiency of biological aerated filter and explore a more simple and accurate design method.

Many studies show that the numerical simulation results of FLUENT software are very similar to the experimental results. Liao Tengyi [5] simulated the Biostyr filter, J. Ridgeman [6] simulated the distribution and reaction of anaerobic bacteria and activated sludge in small-scale experimental equipment, and Ding Rui et al. [7] simulated the hydrodynamic characteristics of self-made water treatment reactor, all of which were consistent with the results of verification experiments. Using FLUENT for reactor design can effectively reduce the workload of repeated experiments and calculation,
and save cost. At present, there are few reports on the application of FLUENT in the denitrification of biological aerated filter. Wang Lijie [8] simulated the influence of water retention time and water vapor ratio on the nitrogen removal efficiency of BAF, but there is no further study on the key design parameters of the filter, such as filler, initial ammonia nitrogen concentration and dissolved oxygen.

In this study, the FLUENT nitrogen removal simulation of the experimental device of biological aerated filter was conducted to explore the particle size of filler, initial ammonia nitrogen concentration, dissolved oxygen and the amount of filler to achieve the highest nitrogen removal efficiency of the small biological aerated filter, and explore the method of numerical simulation to design the biological aerated filter and optimize the nitrogen removal efficiency.

2. Numerical Simulation

2.1. Simulation Object
The simulation object is a rectangular filter with a scale of 70*60*190mm. The height of the lower packing area is 70mm, the height of the upper packing area is 90mm, and the design height of the aeration area is 30mm at the bottom. The two-layer packing zone can effectively slow down the wall flow phenomenon, make the liquid phase more evenly distributed in the tower, and improve the processing efficiency. The packing adopts hollow spherical packing, which has large specific surface area and high space utilization rate, and the regular spherical packing is convenient to simulate. The lower layer is 20mm more than the upper layer to expand the capacity of sewage. See figure 1 for the three views of the tower body. After considering the size and cost of the aeration device, the aeration device was optimized, and the method of aquarium microhole aeration was chosen instead of the herring-shaped guide plate and perforated tube aeration commonly used in BAF. Because this method can not only meet the oxygen demand, but also have a good disturbance effect on the substrate, which is helpful to improve the efficiency of nitrogen removal.

![Figure 1. Design of biological aerated filter experimental device.](image)

2.2. Simulation Method
FLUENT is a commonly used CFD software package, which has strong grid support ability. The finite volume method based on completely unstructured grid is used for simulation calculation. The software contains a wealth of turbulence models, which can accurately simulate inviscous flow, laminar flow, turbulence, etc. ICEM was used to read the three-dimensional filter model designed by CAD, and the triangle mesh was used to divide it. Boundary layer conditions such as inlet, outlet and fluid domain were defined, and the output was MSH file. The mesh file was read by FLUENT, and the Mixture model
of multiphase flow was used to calculate the fluid dynamics. The nebulae of ammonia concentration distribution were output after changing the parameters. The reaction design was the transformation of \( \text{NH}_4^+ \) to \( \text{N}_2 \). The spherical filler was simulated by porous media model. The porosity of porous media was designed to be 0.5, and the size of the filler was characterized by the drag coefficient.

### 2.3. Simulation Experiment

In this simulation process, a total of 7 groups of conditions were designed. Two surface areas \( X \) and \( Y \) were designed in the direction parallel to and perpendicular to the wall where the water inlet was located. By observing the distribution of ammonia nitrogen concentration on the two surface areas, the nitrogen removal efficiency was calculated and analyzed. The first four groups of simulation tests respectively simulated the distribution of ammonia nitrogen concentration on two surfaces under different packing particle sizes, and determined the optimal packing size. In the last three groups of simulation experiments, the group conditions of the optimal particle size obtained in the previous four groups of experiments were taken as reference, and the values of ammonia nitrogen concentration, filler amount and dissolved oxygen in the intake were changed to explore the best parameter conditions. The design inlet and outlet water flow rate is 1m/s. The packing amount is expressed as the proportion of the volume occupied by the packing area.

#### Table 1. Experimental design parameter.

| Group | Packing size (mm) | Inlet ammonia nitrogen concentration (%) | Proportion of packing area occupied (%) | Dissolved oxygen content (%) |
|-------|------------------|------------------------------------------|----------------------------------------|-----------------------------|
| 1     | 10               | 10.00                                    | 60                                     | 1.0                         |
| 2     | 8                | 10.00                                    | 60                                     | 1.0                         |
| 3     | 6                | 10.00                                    | 60                                     | 1.0                         |
| 4     | 4                | 10.00                                    | 60                                     | 1.0                         |
| 5     | required value   | 15.00                                    | 60                                     | 1.0                         |
| 6     | required value   | 15.00                                    | 60                                     | 1.5                         |
| 7     | required value   | 15.00                                    | 70                                     | 1.5                         |

### 3. Results and Discussion

Table 2 lists the numerical simulation calculation results of ammonia nitrogen removal efficiency under 7 working conditions.

#### Table 2. Ammonia nitrogen removal efficiency calculation table.

| Group | Packing size (mm) | Inlet ammonia nitrogen concentration (%) | Outlet ammonia nitrogen concentration (%) | Ammonia nitrogen removal efficiency (%) |
|-------|------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| 1     | 10               | 10.00                                    | 7.65                                     | 23.50                                    |
| 2     | 8                | 10.00                                    | 7.16                                     | 28.40                                    |
| 3     | 6                | 10.00                                    | 6.80                                     | 32.00                                    |
| 4     | 4                | 10.00                                    | 5.75                                     | 42.50                                    |
| 5     | 4                | 15.00                                    | 10.44                                    | 45.60                                    |
| 6     | 4                | 15.00                                    | 4.90                                     | 67.33                                    |
| 7     | 4                | 15.00                                    | 4.66                                     | 68.93                                    |

#### 3.1. Optimum Packing Size

It can be seen from the first four working conditions in table 2 that the smaller the packing size of the spherical filler, the higher the ammonia nitrogen removal efficiency, and the optimal particle size is 4mm. It is concluded that the smaller the packing size is, the larger the specific surface area is, which is
conducive to increasing the mass transfer contact area and prolonging the reaction time, and is conducive to hanging the film in the practical application. Literature reports [9-10] also show that fillers with smaller packing size have better ammonia nitrogen removal performance. But too small packing size will increase the production cost, after comprehensive consideration, this design uses 4mm spherical packing.

3.2. Effect of Influent Ammonia Nitrogen Concentration on Denitrification

The nebulae of concentration distribution in X and Y areas of Group 4 (figure 2) and Group 5 (figure 3) were compared and analyzed. It was found that the content of ammonia nitrogen in the filter decreased significantly after the concentration of ammonia nitrogen was increased, and the overall distribution showed that the content in the upper layer decreased significantly while the concentration in the lower layer was higher. The concentration of nitrogen on the wall side where the sewage inlet is located is high, which may be due to the poor fluidity of the liquid phase, which is harmful to the mass transfer and reaction of oxygen. Table 2 shows that the nitrogen removal efficiency is slightly improved after increasing the concentration of influent ammonia nitrogen. The analysis reason may be that the nitrogen content set in the simulation is within the range that microorganisms can oxidize, and higher concentration of ammonia nitrogen is conducive to the growth of nitrification bacteria. There are also reports in the literature that increasing the nitrogen load within a certain range will increase the nitrogen removal efficiency [11].

3.3. Effect of Dissolved Oxygen on Denitrification

By comparing and analyzing the cloud map of concentration distribution in X and Y plane of Group 5 (figure 3) and Group 6 (figure 4), it is found that: it was found that when dissolved oxygen was appropriately increased, the concentration of ammonia nitrogen at the outlet was significantly reduced. According to the calculation results in table 2, compared with Group 5, the dissolved oxygen content in group 6 only increased by 0.5%, and the nitrogen removal efficiency increased by 21.73%, indicating that the change of dissolved oxygen had a significant impact on the nitrogen removal efficiency. This is because dissolved oxygen will not only affect the growth of nitrification bacteria, but also affect the gas-liquid two-phase flow field of the BAF [12] and the shear action on the surface of the biofilm [13]. This design uses 1.5% oxygen content with high nitrogen removal efficiency.

Figure 2. Nebulogram of concentration distribution in X and Y plane of group 4.

Figure 3. Nebulogram of concentration distribution in X and Y plane of group 5.
3.4. Effect of Packing Quantity on Denitrification

Group 7 increased the packing amount by 10% on the basis of Group 6. According to the concentration distribution nebularograph (Figure 3 and Figure 4), the ammonia nitrogen concentration at the outlet of Group 6 and Group 7 was significantly reduced, but there was no significant difference between them. According to the calculation results, the nitrogen removal efficiency of Group 7 only increased by 1.6% when the filler was increased by 10%, which indicated that increasing the filler amount within the allowable range of the filter load was beneficial to increase the ammonia nitrogen conversion efficiency. The analytical reason may be that increasing the filler amount properly could provide more space for microbial attachment and growth. However, the improvement of nitrogen removal efficiency is not very obvious. Due to cost considerations, the BAF is designed to take up 60 percent of the total packing area volume when running.

3. Conclusion

After optimizing the packing area and the aeration unit, the final design of the small biological aerated filter was a tower BAF with two layers of packing and aquarium microporous aeration. The numerical simulation of self-made small biological aerated filter by FLUENT shows that the decarburization efficiency is higher with the smaller particle size of filler. Dissolved oxygen concentration has great influence on the BAF operation and appropriate increase of dissolved oxygen can significantly improve the effect of nitrogen removal. With the increase of influent ammonia nitrogen concentration and filler amount, the nitrogen removal efficiency is increased but the effect is not obvious. The optimal design parameters of the small biological aerated filter in terms of packing particle size, packing quantity, initial ammonia nitrogen concentration and dissolved oxygen are 4mm, 60%, 15% and 1.5% respectively. Under these parameters, the ammonia nitrogen removal efficiency of 67.33% can be achieved, which is about 30% higher than that reported in the literature [4]. The FLUENT numerical simulation method was used to design the biological aerated filter and optimize the nitrogen removal efficiency, which provided a reference for the experimental research and practical application of nitrogen removal in biological aerated filter.

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