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Simulation and Research of CFD on Internal Pressure Parallel Hollow Fiber Membrane Module

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Abstract: **Membrane bioreactor (MBR) has been widely used in sewage treatment, effectively solving many long-standing problems such as solid-liquid separation. In this paper, the internal pressure parallel type hollow fiber membrane module was taken as the research object. Based on the CFD theory and method, the solid-liquid separation of the flow entering the membrane module was simulated by FLUENT software. Firstly, the geometric model of the internal pressure parallel membrane module was established by the computational fluid dynamics (CFD) preprocessor and structured meshing was performed. Then the volume fraction of suspended solid (SS) at the exit of the model was calculated by Eulerian multi-phase flow model and Phase Coupled SIMPLE algorithm. The calculation results were presented as images in the CFD post processor. In this paper, the simulation calculation for different concentrations of suspended solid showed that the volume fraction of suspended solid at the exit of the model was zero, which was consistent with the actual MBR system operating data. The simulation results indicated that the model established in this paper had higher accuracy. The model can simulate and predict the separation effect of solid-liquid two-phase flow in wastewater treatment, which has certain reference value for MBR engineering design and research.**

Keywords: **MBR; CFD; Eulerian multi-phase flow model; solid-liquid separation; SS**

I. Instruction

Membrane bioreactor (MBR) has the advantages of good effluent quality, low operating cost, strong system impact resistance, low sludge volume and high degree of automation [1-2]. The presence of the MBR membrane increases the ability of the system to separate solid and liquid, bringing about a significant increase in system effluent, water quality and volumetric loading. Due to the filtration of the membrane, the microorganisms are completely trapped in the MBR that achieves complete separation of water and activated sludge and eliminates the problem of sludge expansion in the traditional activated sludge process [3-4].

Computational fluid dynamics (CFD) is a numerical simulation tool developed with modern computer technology [5]. CFD plays an important role in fluid mechanics, momentum, heat, mass transfer and reaction, multiphase flow and some complex system research. What’s more, it has been widely used as a core technology in research and development of technologies and equipment in many engineering fields such as aerospace, automotive, water conservancy, chemical and environmental engineering [5-7]. At the same time, MBR also has some problems that are difficult to solve: complex structure, variable operating conditions, difficult experimental research, high cost, long time and limited experimental results. CFD has the characteristics of less capital investment, fast calculation speed, complete information and strong simulation ability, and is not affected by the size and structure complexity of the research object [8-10].

MBR is one of the popular fields of sewage treatment, and has broad application prospects. At present, CFD has been widely used in structural simulation and optimization of MBR [3]. This paper built the MBR membrane module by the CFD tool and achieved the separation of solid-liquid two-phase flow. The CFD provides detailed analysis of the flow field and macroscopic diffusion of materials within the system [11-12]. This article modeled and simplified assumptions for a single filament or a part of the module geometry, reducing computational time.

II. Research Object

A. Membrane Module

The membrane module is the indispensable part of the MBR. According to the structure, the membrane can be divided into four types: hollow fiber, flat, spiral and tubular membrane[13-14]. The four membranes have different characteristics and the scope of application is also different. The difference is shown in Table 1.

Table I. The comparison table of four membrane

	Hollow fiber	Flat	Spiral	Tubular
Loading density	high	medium	medium	low
Operating energy consumption	low	medium	medium	high
Equipment prices	low	high	low	high
Membrane change cost	medium	low	medium	high
Backwash	yes	no	no	no

B. MBR System

1) Internal and external pressure MBR system

In the MBR system, the hollow fiber membrane module can be divided into an internal pressure MBR system and an external pressure MBR system according to the operation mode, as shown in Figure 1.

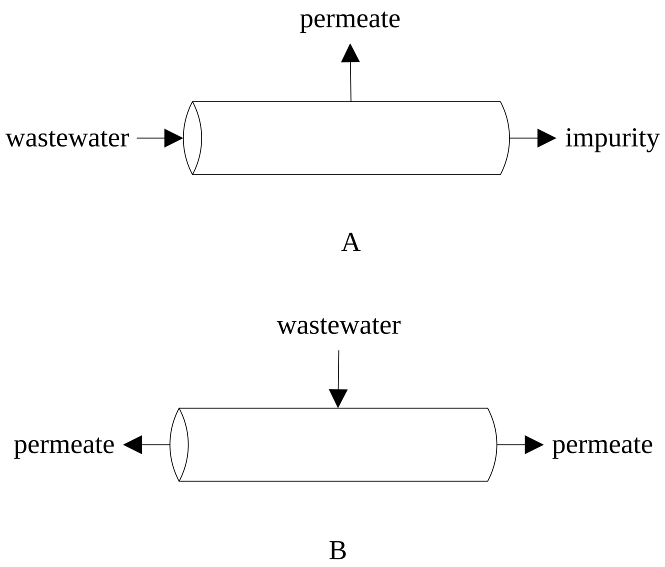


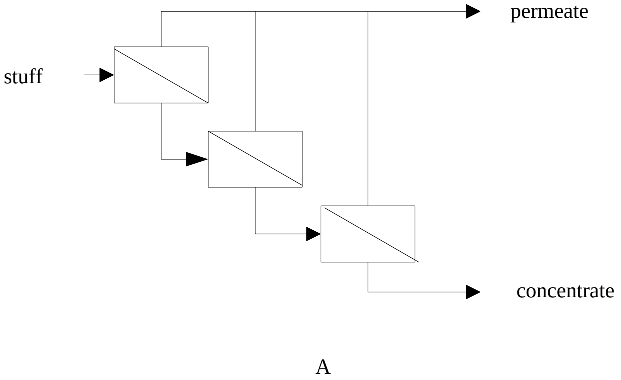
Figure I. (A) Internal pressure MBR; (B) External pressure MBR.

Internal pressure MBR system: when the MBR system is operated, the pretreated sewage flows from one end of the hollow fiber tube. After filtration, the filtrate is out from the hollow fiber tube wall. The impurities such as SS in the sewage flow out from the other end of the hollow fiber tube.

External pressure type MBR system: the operation mode is opposite to the internal pressure type MBR system. When the MBR system is operated, the pretreated sewage flows from the hollow fiber tube wall. After filtration, the filtrate flows out from both ends of the hollow fiber tube. And the impurities such as SS are trapped on the tube wall.

2) Series and parallel connection MBR

The MBR system can be divided into a series MBR system and a parallel MBR system from the connection mode, as shown in Figure 2.



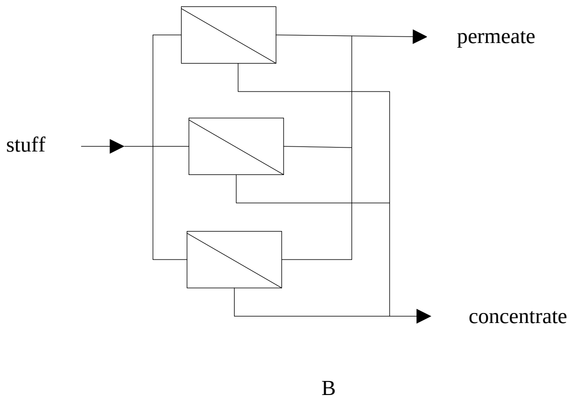


Figure II. (A) Series connection method; (B) Parallel connection method.

Series MBR system: when the series MBR system treats sewage, the sewage flows through the membrane modules of each stage one by one. The filtrate is collected at the last stage membrane module.

Parallel MBR system: when the parallel MBR system is running, the sewage flows through each membrane module at the same time, and finally the filtrate is collected uniformly. These two MBR systems are equivalent.

III. Modeling method and CFD modeling process of internal pressure parallel MBR

A. Calculation Methods and Conditions

1) Mathematical model

When the membrane module is simulated by FLUENT software, the Eulerian bidirectional flow model is adopted. And the general form of the control equation is as follows.

Mass conservation equation:

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot \left(\alpha_q \rho_q u_q\right) = 0 \tag{1}$$

Where a_q is the volume fraction; ρ_q is the density, kg · m^{-3}; ρ_q is the average velocity vector of the qth phase, m · s^{-1}; q denotes the liquid phase or solid phase g.

Momentum conservation equation:

$$\frac{\partial\, \alpha_q \rho_q u_q}{\partial t} + \nabla g\left(\alpha_q \rho_q u_{qj} u_q\right) = -\alpha_q g \nabla p_q + \nabla g\left(\alpha_q \tau_q\right) + F_q + \alpha_q \rho_q g \tag{2}$$

Where q represents liquid phase (water) or gas phase (air); j represents three directions of x, y, z; t is time, s; a_q is volume fraction; u_q is flow velocity, m · s^{-1}; ρ_q is density, kg · m^{-3}; p_q is the pressure, Pa; τ_q is the viscous stress tensor, Pa; F_q is the interphase force of the micro-element, N · m^{-3}; g is the gravity Acceleration, m · s^{-2}.

2) Calculation conditions

The MBR membrane module was simulated by FLUENT software for solid-liquid two-phase flow. Due to the Reynolds number was lower than 2300, the laminar flow model was selected. And the Eulerian model was used as the two-phase flow model. To simplify the calculation, the liquid phase was clean water and the solid phase was set as a suspended solid in the two-phase flow. The initial flow rate of the solid suspension phase and the liquid phase both were set to zero. The inlet boundary condition was defined as the pressure inlet, the velocity direction was perpendicular to the inlet boundary. It was assumed that the sand at the inlet had the same velocity as the water, and the outlet boundary was defined as the pressure outlet. The geometric model was segmented using a structured grid with a standard wall function. In order to make the calculation better, the sub-relaxation factor could be appropriately reduced. The convergence precision was 0.0001, and the number of single-step iterations was 2000.

B CFD Modeling Process

1) ICEM CFD establishes internal pressure parallel MBR and meshing

The geometric model established by the ICEM CFD preprocessor in this paper is shown in Figure 3, which represented a two-stage parallel MBR system. Only the operation of a single hollow fiber membrane wire was studied on the water tank of each stage of the MBR system. The small cylinder on each membrane tube represented the small hole in the wall of the membrane tube. When the MBR system was running, the sewage flowed into the water pipe from the water inlet. After passing through the water tank of each stage, the permeate flowed out from the small hole in the wall of the membrane tube and flowed out from the outlet 1. The solid particles in the sewage were separated from the outlet 2.

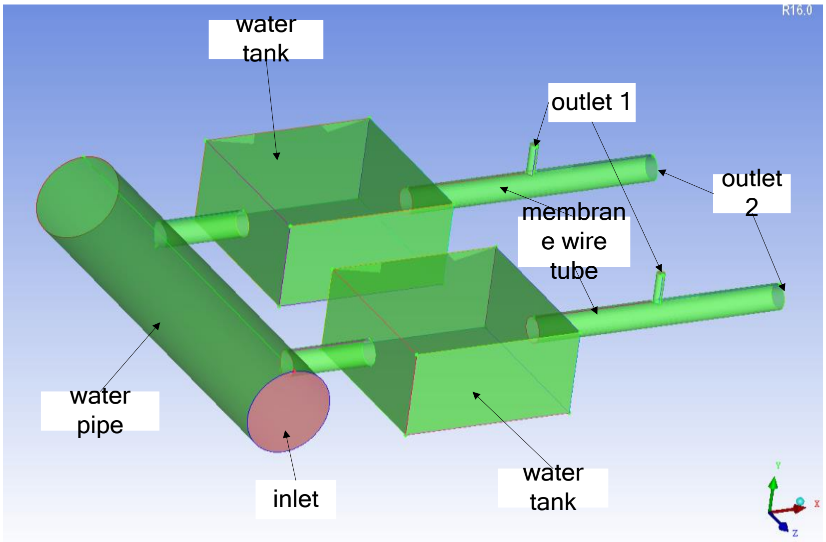


Figure III. Two-stage parallel MBR model diagram.

In ICEM CFD, there are two types of meshing: structured meshing and unstructured meshing. Structured meshing usually divides the geometric model into several quadrilaterals or hexahedrons; unstructured meshing usually divides the geometric model into several triangles or tetrahedrons. The specific method of partitioning depends on the actual situation. Because the texture distribution of the hollow fiber membrane tube is uniform, this paper used structured meshing. The circular part was O-shaped, and the final grid file was shown in Figure 4. Figure 5 showed the grid quality map of the grid file, where the minimum grid quality is 0.401.

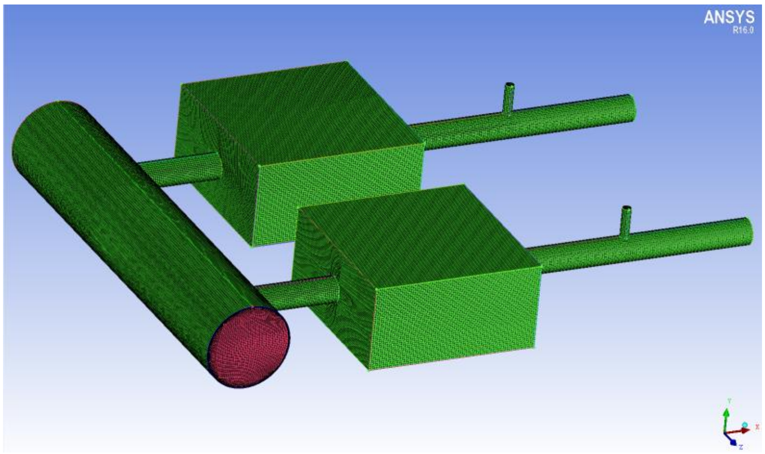


Figure IV. Geometric model grid diagram.

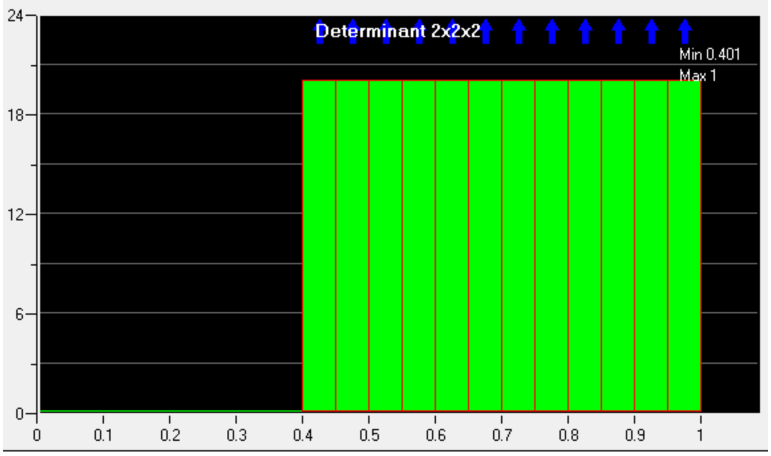


Figure V. Determinant 2 × 2 × 2 grid quality.

2) Fluent solver calculation

In the FLUENT solver, the FLUENT model operation tree is mainly composed of solution model description, solution process control and post-calculation processing. Only the first two parts were used in this paper. The solution model description is mainly used to set the initial conditions for the calculation model. After importing the grid file into the FLUENT solver, the first step was to check the grid file for ensuring that the minimum volume was not negative. Transient solver was selected which based on the pressure in the model tree and set the acceleration of gravity. The second step was to select the physical model. Because the research object of this paper was solid-liquid separation, the Eulerian multiphase flow model was selected. The Reynolds number was calculated according to the formula (3). In the third step, water was introduced into the material library as a fluid material. The SS material was established through actual data. The fourth step set the primary and secondary phases. Since the SS was dispersed in the water, the water was the main phase and the SS was the secondary phase. In the fifth step, the inlet and outlet boundary conditions were set. In this paper, the pressure inlet was set as the inlet boundary condition. The volume fraction of SS was input in the secondary phase inlet boundary condition. the pressure outlet was set as the outlet boundary condition. The work of setting solution model description had been completed. The setting of solution process control was performed below.

$$\mathrm{Re} = \frac{\rho u L}{\mu} \qquad (3)$$

Where ρ denotes fluid density; u means flow rate; L means characteristic length; μ represents dynamic viscosity.

In the solution process control model tree, Phase Coupled SIMPLE algorithm was first selected as the solution algorithm, in which the gradient was set to Least Squares Cell Based. The momentum equation and the volume fraction were set to the First Order Upwind. The relaxation factor was set to remain the default. The volume fraction of suspended solids was monitored at the exit of the hollow fiber membrane coil. Finally, the model was initialized and began the iterative calculation. Figure 6 was a residual graph of the solver iterative calculation. Convergence reached at the iteration of 79 steps. Fig. 7 indicated the volume fraction of suspended solid at the exit of the hollow fiber membrane tube. It was not difficult to see that the volume fraction of suspended solid at the outlet was substantially zero with the iterative calculation of the solver. The effect of solid-liquid separation is achieved.

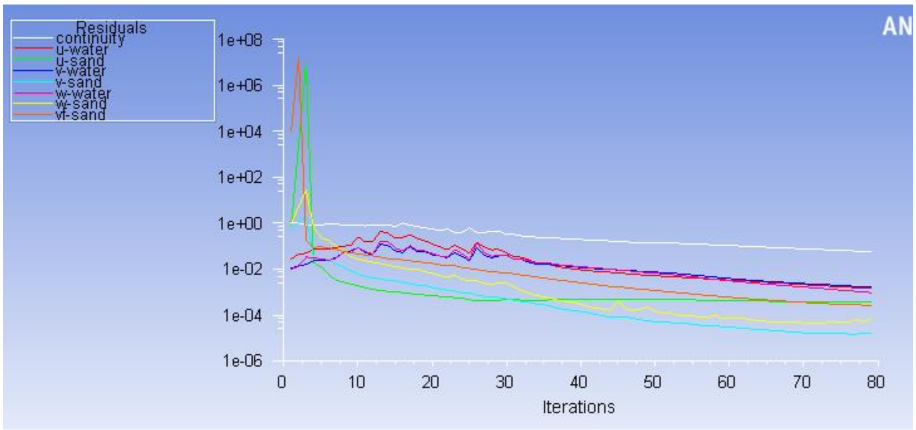


Figure VI. Residual curve.

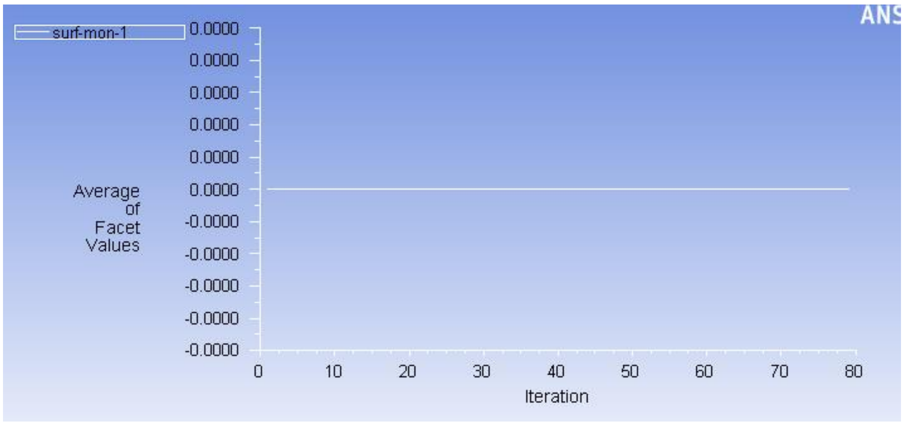


Figure VII. The volume fraction of suspended solid.

3) Post-processing cloud image display

This paper used CFD post-processor to perform post-calculation operation for expressing the calculation result as graphics or image. On the other side of the water pipe was sealed in Figure 9. Due to the reaction force at the seal, the pressure at the seal of the water pipe increased when the sewage flowed from the water pipe to the other side, which was consistent with the principle of the actual MBR system. By observing Figure 10, it found that the speed of SS at the exit was basically zero, which was basically consistent with the actual MBR system operation result. It realized the effect of solid-liquid separation and solved the problem of to simulate the internal parallel MBR system for filtering sewage.

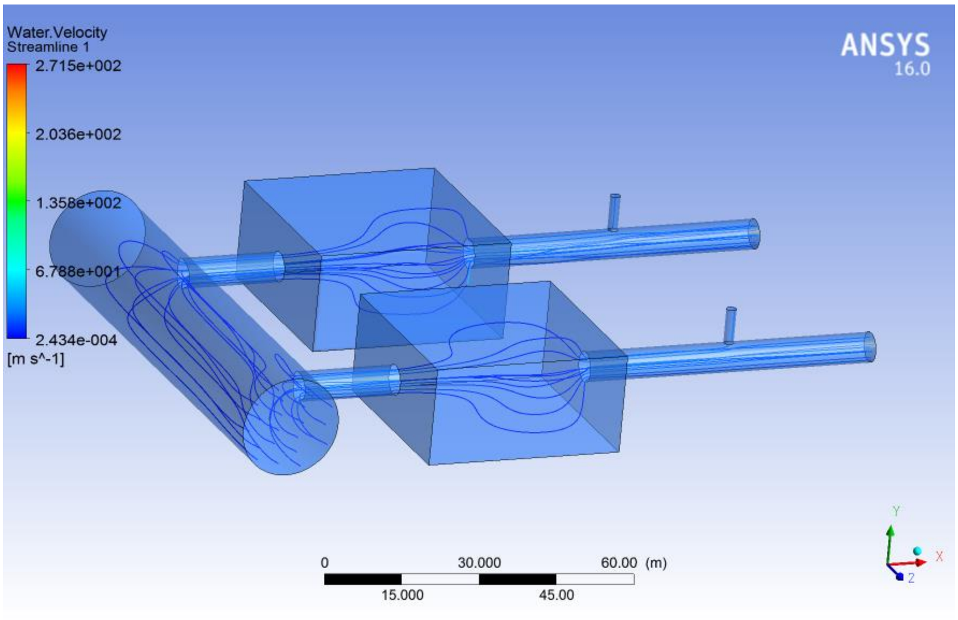


Figure VIII. Streamline diagram of water: This is the flow of liquid water in an internal pressure parallel MBR model. The color bars on the left indicates the flow rate of water, which decreases from top to bottom.

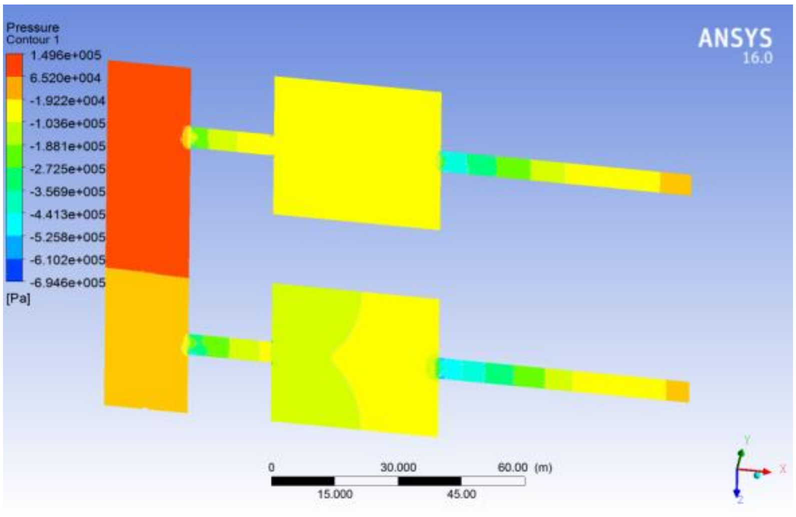


Figure IX. Pressure cloud diagram of the model section: This is the pressure cloud diagram at the XZ section of the model. The color bar indicates the pressure which is reduced from top to bottom.

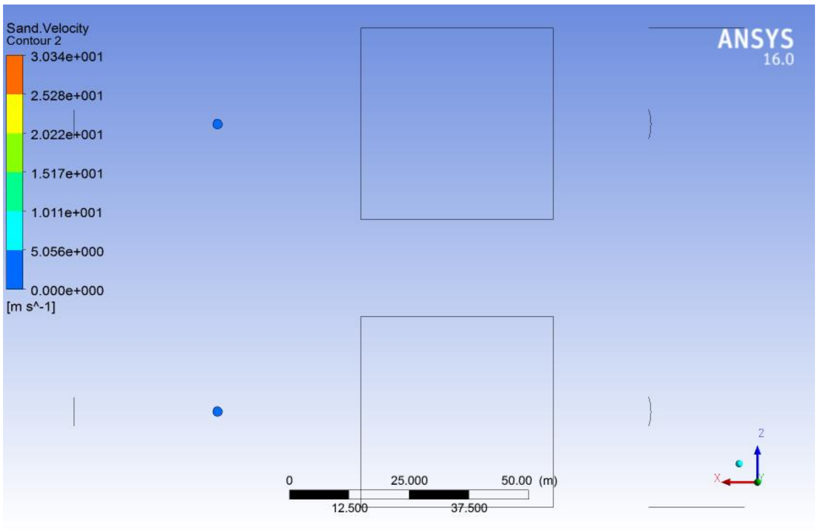


Figure X. Speed cloud map of SS at the exit: This is the velocity cloud diagram of the suspended solid at the outlet of the internal pressure parallel MBR. The color bars on the left side indicates that the velocity decreases from top to bottom, and the minimum velocity is zero.

IV. Simulation results analysis

In order to verify the correctness and reliability of the above CFD model, this paper selected the actual MBR system operation data of a sewage treatment plant in Shijiazhuang for analysis. In the analysis processing, we selected sewage with different concentration of SS as the experimental sample. The different concentration of SS as the secondary boundary condition of the solver to calculate iteratively. Table 2 displayed the comparison between the simulation results and the actual MBR system operation results. The different concentrations of SS were calculated by Eulerian multi-phase flow model, the volume fraction of SS at the exit is basically zero. It was basically consistent with the operation result of the actual MBR system. The comparison results showed that the internal pressure parallel membrane module model established by CFD was correct and reliable. The calculation results also demonstrated that the internal pressure parallel MBR system could be used to filter out the solid suspended particles in the actual production.

Table II. The amount of change in SS in the membrane module

Influent volume	Initial SS concentration	Actual SS concentration	Simulation SS concentration
2	282	0	0
2	147	0	0
2	214	0	0
2	200	0	0
2	87	0	0
2	364	0	0
2	298	0	0
2	223	0	0
2	225	0	0
2	294	0	0
2	359	0	0
2	277	0	0
2	191	0	0
2	143	0	0
2	269	0	0
2	127	0	0

V. Conclusion

In this paper, the tool of CFD was used to establish the MBR system model of the internal pressure parallel membrane module. The model was applied to simulate the solid-liquid separation for the sewage entering the membrane module. Using this model, a large number of simulation calculations were performed on different concentrations of SS. Compared with the actual data in a sewage treatment plant, the comparison showed that the data obtained by the internal pressure parallel MBR model established was basically consistent with the actual data. The pressure cloud and streamline diagram of the post-processor displayed the working condition of the MBR system, so that we could clearly observe the flow of sewage and the situation of stress in the membrane module. The simulation results indicated that the internal pressure parallel MBR model established by CFD is correct and reliable. The internal pressure parallel MBR system can be applied to the actual production of sewage treatment. Applying computational fluid dynamics to MBR system modeling and simulation is also a novel research idea and method. It can not only save a lot of MBR engineering design and engineering implementation cost, but also has certain reference value for MBR field research.

Acknowledgements

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