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Application of numerical simulation on optimum design of two-dimensional sedimentation tanks in the wastewater treatment plant

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Abstract: The paper establishes the relationship between the settling efficiency and the sizes of the sedimentation tank through the process of numerical simulation, which is taken as one of the constraints to set up a simple optimum designing model of sedimentation tank. The feasibility and advantages of this model based on numerical calculation are verified through the application of practical case.

Keywords: numerical simulation; sedimentation tank; optimum design

Introduction

The sedimentation tank is one of the essential parts in the wastewater treatment process and holds about 25 percent of the total investment cost of wastewater treatment plant (Chatellier, 2000). Therefore, the optimum design of sedimentation tank is of far reaching importance for saving investment, reducing operating expenses and so on. The traditional sedimentation tank is designed according to the surface load, which has a negative feature of strong subjectivity. This paper aims to simulate the concentrations of water flow and suspended solids in sedimentation tanks by using the method of numerical calculation. Thus the non-linear relationship between the treatment efficiencies and the sizes of the sedimentation tank could be established. The optimum designing sizes of the sedimentation tank could be obtained by the solution of the optimum model.

1 Numerical simulation of sedimentation tanks

In the past twenty years, the researches on the simulation of sedimentation tanks mostly focused on two-dimensional ones. Some scholars such as Schamber and Larock (Schamber, 1981), Imam *et al*. (Imam, 1983), Adams and Rodi (Adams, 1990) and so on had made lots of research efforts on the simulation of two-dimensional primary sedimentation tanks by turbulent flow models. Generally, though the water flow in sedimentation tank is three-dimensional, it is also feasible to make two-dimensional simulation due to the reason that more considerations of the velocity influences in vertical section on suspended solid transport should be taken into account during the simulation process (Imam, 1983a; b).

1.1 Calculation zone

The scheme of construction of a typical horizontal flow in the rectangular sedimentation tank and its idealized domain are omitted in this paper, which is shown in the literature by Zeng *et al*. (Zeng, 2003).

1.2 Governing equations

For a two-dimensional turbulent flow of an incompressible Newtonian fluid, the governing equations of motion and continuity can be written as the following normalized vorticity transport and stream function formulation (Imam, 1983a; b):

Vorticity transport function

$$\frac{\partial \omega}{\partial t} = -\frac{\partial(u\omega)}{\partial x} - \frac{\partial(v\omega)}{\partial y} + \frac{1}{Re}\nabla^2 \omega. \tag{1}$$

Stream function $$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = \omega. \tag{2}$$

The vorticity is defined by

$$\omega = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}. \tag{3}$$

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The stream function is defined by

$$\frac{\partial \psi}{\partial y} = u, \frac{\partial \psi}{\partial x} = -v, \tag{4}$$

in which u, v are the normalized velocity in x, y direction respectively; Re is the characteristic Reynolds number based on eddy kinematic viscosity; H is the defined as the tank depth, and U as the average horizontal flow velocity, which are set as characteristic length and velocity respectively; u, v, Re are defined as $u = u'/U$, $v = v'/U$, and $Re = HU/v_t$ respectively, where u', v' are actual velocities.

1.3 Dispersion of governing equations

The grid division of the computing domain is shown in Fig. 1.

Fig.1 shows a $m \times n$ grid system. According to the boundaries and references(Tao, 1991; Imam, 1983a; b; Zeng, 2003), the boundary conditions ψ_i, ω_i ($i = 1$—5) of boundary B_1—B_5 could be determined.

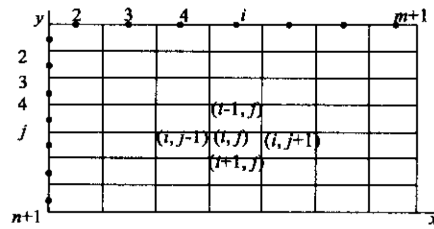

Fig.1 Grid system of x, y direction

Normally, the finite difference method is adopted to solve the vorticity transport and stream function because of the nonstationarity, nonlinearity and complex boundary conditions of the functions. To different conditions, variant finite difference schemes could be selected. This paper uses the implicit windward finite difference method with Alternative Direction Implicit(ADI) to disperse the vorticity transport equation(Zhao, 1987) and uses Gauss-Seidel iteration method(Lu, 1988) to disperse the stream function. Details could be found in relevant references. The procedures of the finite difference method are listed as follows: (1) divide the computing zone into finite difference grids; (2) find the boundary conditions. For non-stationary flow, the initial conditions at $t = 0$ should also be given; (3) solve the vorticity transport Eq.(1) by finite difference method. The value of can be obtained from ψ^n which is already known; (4) taking above ω^{n+1} as given values, solve the stream function (2) to get a new stream function value of ψ^{n+1}; (5) renew the vorticity boundary values; (6) repeat above procedures until the stream function value be convergent. Then calculate the flow velocities u, v and concentration in every node point by concentration functions.

2 Optimum design method for sedimentation tanks based on numerical calculation

The first step of the traditional designing method for sedimentation tanks is to get the surface load u_0 from settling experiment. Then determine the surface area A of the sedimentation tank by Formula (5) written as

$$A = \frac{Q}{u_0}, \tag{5}$$

in which Q is the wastewater flows volume. Finally, determine the length, width and depth of the sedimentation tank. In actual sedimentation tanks, the conditions are more complicated than ideal ones which means the actual settling time is longer than theoretical ones to reach certain settling efficiencies(Zhang, 1998). In such a manner, safety coefficients are required which is given as

$$q = \left(\frac{1}{1.25} - \frac{1}{1.75}\right) u_0, \tag{6}$$

in which q is the designing surface load. So it will be seen that large subjectivity exists in designing the sedimentation tank by surface load, which need to be improved.

In recent years, some scholars have presented some optimum design models for sedimentation tanks. These models considered the controlling factors of designing the sedimentation tank from different point of view, which could provide helpful references for the design of sedimentation tanks more rationally(Swamee, 1996).

The cost function of the sedimentation tank is related to its surface area. For primary sedimentation tanks, the cost function can be defined as

$$C = \alpha_1 A^{\beta_1} + \alpha_2 A^{\beta_2}, \tag{7}$$

in which C is the total cost, A is the surface area, and α_1, β_1, α_2, β_2 are the statistical coefficients of the cost; the first item on the right side of the cost function is construction cost, and the second is operating cost.

This paper aims to establish a simple optimum design model of sedimentation tank by means of numerical calculation, among which the main procedures are listed as follows:

(1) Determination of the relationship among the length L, the depth H and the treatment efficiency η through numerical calculation

To specific influent water quality conditions (flow volume Q, concentration of suspended solids C), use the two-dimensional numerical simulation method to figure out the effluent suspended solid concentration C_{out} through the process of changing L the length and depth H. Afterwards, a series of discrete data related to the relationship between above three items can be acquired. Define the initial concentration of suspended solid as C_0. The settling efficiency can be obtained by

$$\eta = \frac{C_0 - C_{out}}{C_0}. \tag{8}$$

The length L, depth H and treatment efficiency η of the sedimentation tank have a complicated non-linear relationship. Through the process of curve fitting, a non-linear function written as follows can be found to represent such relationship between the three items from the large discrete data.

$$\eta = f(L, H). \tag{9}$$

Then, Formula (9) can be taken as one of the restraints in the optimum model.

(2) Establishment of the optimum model

From above discussion, the objective function, namely cost function shown in Formula (7), and the restraint conditions can be established respectively. The restraint conditions consist of the effluent water quality constraints and the upper and lower limits of the decision variables mainly including the sizes of the sedimentation tank and so on. Here, only the geometrical sizes of the sedimentation tank are considered rather than the subjective surface load determined by experience, which may be one of the advantages of the numerical simulation method.

The optimum model could be written as

$$\mathrm{Min}\, C = \alpha_1 A^{\beta_1} + \alpha_2 A^{\beta_2}; \tag{10}$$

$$\begin{cases} H_{min} \leqslant H \leqslant H_{max} \\ r_{min} \leqslant \dfrac{L}{W} \leqslant r_{max} \\ C_{min} \leqslant C \leqslant C_{man} \\ \eta_{min} \leqslant \eta = f(L, H) \leqslant \eta_{max}, \end{cases} \tag{11}$$

in which W is the width of the sedimentation tank, r is the ratio of the length and depth. The optimum sizes of the sedimentation tank(L^*, H^*, W^*) can be acquired by solving the non-linear programming model.

3 Example of application

A factory has a flow volume $Q = 8000\ \mathrm{m^3/d}$ of industrial wastewater, and the concentration of suspended solid is $C_0 = 1600$ mg/L. The concentration of effluent suspended solid is required to be lower than 80 mg/L after treatment. Design the best sizes of the sedimentation tank.

Firstly, according to the influent water quality condition, use the two-dimensional numerical simulation method to figure out a series of discrete data about the relationship between the sizes and efficiency by changing the length L and depth H. This paper calculated about 500 groups of data, which will not be listed limited to the space of the paper. Through the process of curve fitting, the functional relationship can be written as

$$\eta = \exp\left(\frac{0.065 - H/L}{0.20}\right). \tag{12}$$

The lowest requirement of the efficiency is $\eta_{min} = (1600 - 80)/1600 = 95\%$. Only construction cost is concerned in the cost function and the upper and lower limits of some parameters can be found in the reference(Wang, 1992). The optimum model could be established as follows:

$$\mathrm{Min}\, C = 0.6929 A^{0.88};$$

$$\begin{cases} 4 \leqslant L/W \leqslant 5 \\ 95\% \leqslant \exp\left(\frac{0.065 - H/L}{0.20}\right) \leqslant 100\% \\ 1 \leqslant H \leqslant 3 \\ A = WL \end{cases}.$$

After calculation, the result is

$L^* = 14$ m, $H^* = 1.5$ m, $W^* = 2.8$ m, $A^* = 39.2$ m^2, $C^* = 1.75 \times 10^5$ RMB Yuan.

The traditional designing process is introduced as follows:

Define the particle sedimentation rate $V_s = 0.033$ cm/s, the depth of the sedimentation tank $H = 2$ m, and the ratio of length and width is $K = 4.8$. The length W of the sedimentation tank could be determined by Formula (13) as (Design Handbook, 1994)

$$W = \left(\frac{HQ}{V_s K^2}\right)^{1/3}. \tag{13}$$

After calculation of Formula (13), the result is $W = 3$ m, $L = 14.4$ m, $A = 43.2$ m^2, and the construction cost is 19.1×10^5 RMB Yuan. Obviously, the numerical method saved about 9.2% of the total investment compared with traditional method, and the sizes is more reasonable and accurate. The empirical designs mostly have certain safety coefficients to resist the sporadic disasters, which could probably reach or even exceed the result of numerical method. However, the empirical method is uncertain and always lead to different results by different designers. The numerical design method is more objective and direct though the result is not entirely determined and accurate due to the complexity of practical cases and model errors.

Certainly, the practical situations are more complicated. The application of this paper is only a simple example, which needs further research and exploration. The optimum design of the sedimentation tanks by numerical method only need size optimizing process instead of considering the surface load, which reduces the subjectivity of the traditional designing method and provides great guiding significances for the design of the sedimentation tank in waste water treatment plant.

4 Conclusions

Using the equation groups of the vorticity transport and stream function can simulate the concentration distribution of the sedimentation tank. Then the settling efficiency can be figured out under certain conditions. Accordingly, the relationship between the sizes and efficiency of the sedimentation tank will be found, which could presents foundations for the optimum design.

It is only a preliminary exploration for the optimum design of the sedimentation tanks by numerical method that aims to find a new and more accurate approach for designing. The model introduced in this paper is only a simple example, which explains the procedures of the model establishment and the foreground of the numerical analysis. However, the model needs to be verified and modified repeatedly before putting it into use.

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