Study on Simulation Method of Filtration for Oily Wastewater Treatment in Oilfield

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Abstract. Aiming at the filtration system in oily wastewater treatment, based on the simulation accuracy of wastewater treatment, the filtration process in wastewater treatment is numerically simulated, the corresponding mathematical model is established, and a hybrid modeling method combining trajectory tracking and network model method is proposed. Based on the analysis and calculation of the mechanical properties of suspended particles in the filter media, considering the coupling relationship between particles and channels, the dynamic displacement and the changes of channel diameter caused by the filtration process, the determination of channel diameter under different arrangement of filter media, the stress types of suspended particles in the channel, the establishment of mechanical model and the distribution of particles in the channel are studied in detail. Through the distance between the particle centre and the channel, it can be judged whether a particle can be adsorbed. From microcosmic to macroscopical, through the concentration calculated by mathematical model of particles and oil, the change rule and filtration effect of suspended particles and oil in the filtration process are obtained. This paper can increase the researchers' understanding of the trajectory tracking method, improve the accuracy of the proportion of filter materials in the research process of oily wastewater treatment technology, so as to obtain reliable filtration parameters of the target suspended solids.

1. Introduction

Water injection is the main way of oilfield development in China, which makes the produced fluid contain a lot of particles, oil and chemicals[1]. Oilfield wastewater treatment is to purify the oily wastewater treated by oil transfer station, dehydration station and combined station through sedimentation, filtration and other means, so as to achieve the required water quality index and reinjected into underground for reuse [2]. Obviously, treatment effect has a direct impact on the oilfield production and environmental protection [3]. The research on the mechanism of oily wastewater filter tank and the establishment of wastewater purification and filtration model will reveal the process and law of wastewater treatment, which is of great significance to improve the effect of oilfield wastewater treatment.

At present, the domestic research on the filtration system, mainly through the flow field analysis method to optimize the structure of the filtration process to achieve a certain purification effect. For example, Zhang Fengyu [4] improved the filtration efficiency by optimizing the structure of the filter tank. Yin Hongjun [5] improved the filtration efficiency by optimizing the key parameters of different processes. Although some progress has been made in this field, most of the scholars directly use the
methods and theories in other fields. They don’t dig out the displacement and adsorption characteristics of oil particles and suspended solids in the filtration process according to the particularity of oil in oilfield wastewater, and rarely establish the accurate mathematical model of the system. The modeling and Simulation Research of the whole oily wastewater filter tank is still far behind other fields. Through the cooperation with the urban water research center of University of California, Irvine, this paper proposes a modeling method combining trajectory tracking method and network model method, striving to establish a perfect system filtration model, and through the combination of field and laboratory, in-depth analysis of simulation results, verify the descriptive effect of the model on sewage purification.

2. Filter principle and basis
After sedimentation, 70-80% of the oil and suspended particles will be removed, but there is still a certain gap with the reinjection water quality of the oilfield, and the particles are smaller and flocculent [6]. During the filtration, the diameter of the filter material channel will also change when the particles are adsorbed. By updating the mathematical model parameters to simulate the filtration process, the high-precision simulation calculation can be achieved. As shown in ‘Figure 1’, when the filter materials in the filter tank are evenly arranged, the pores can be regarded as a network structure. By calculating the movement trajectory of particles in the channel, we can analyze whether the suspended particles or oil droplets are adsorbed.

![Figure 1. Network model](image)

Specifically, as the particles are continuously deposited and adsorbed in the network model, the diameter of the channel will change. When each batch of particles are adsorbed or flow out from the outlet of the network model, the diameter of the channel in the mesh structure should be calculated circularly until the boundary conditions of filtration time or filter tank blockage are reached. After the end of the simulation, the filtration efficiency and concentration of the filtration model will be obtained.

3. Model establishment
The movement of particles in the filter tank belongs to Brownian motion, which is affected by gravity, van der Waals force and electric double layer force. Particles will move by the action of force. As a result, it is either adsorbed on the channel wall or moved to the next channel through the channel. Before the particles enter the mesh model, a random distance between the particles and the channel wall is generated. We judge whether a particle can be adsorbed by calculating the distance between the particle center and the channel. When the displacement of the particle due to the force is greater than the distance between the particle and the channel wall, it will be adsorbed, otherwise it will enter the lower channel.
This adsorption will take place anywhere in the channel at any time. In the model, the interaction between suspended particles and suspended particles is ignored.

3.1. Establishment of channel
In the filter tank, there are two kinds of maximum probability of filter material arrangement: Triangle accumulation and square accumulation, as shown in ‘Figure 2’ and ‘Figure 3’. The diameter of the channel is calculated by the method of hollow cut inner circle, and the diameter of the triangle accumulation pore is \( d = 0.1547D\), which is the smallest diameter in the network model channel [7]; the diameter of the square accumulation pore is \( d = 0.414D\), which is the largest diameter of the model channel.

![Figure 2. Triangle accumulation](image)

![Figure 3. Square accumulation](image)

In the model, the channel diameter \( d \) ranges from \( 0.1547D \) to \( 0.141D \). The channel size in the whole model will gradually decrease from top to bottom.

3.2. Forces on particles
As mentioned above, the particles receive gravity, van der Waals force and double layer force in the channel. The calculation of these three forces is as follows[8]:

Gravity

\[
F_g = \frac{4}{3} \pi r_p^3 (\rho_p - \rho) g
\]

Double layer force

\[
F_{DL} = \frac{1}{2} \varepsilon_m \varepsilon_0 \rho_p \left[ \frac{2 \varphi_1 \varphi_2 - (\varphi_1^2 + \varphi_2^2)}{1 - e^{-2kr}} \right] e^{-kr}
\]

Van der Waals

\[
F_{LO} = -\frac{2 H_{pwc}}{3} \frac{1}{r_p} \left( \frac{H^2 + 2H}{2r} \right)
\]

\[
H = \frac{2r}{d_p}
\]

3.3. Forces on particles
Under the combined action of the three forces, the displacement of particles in the channel changes in real time:

\[
\Delta L_y = \left[ \frac{F_g}{m_p \beta_i} + \frac{F_{LO}}{m_p \beta_i} + \frac{F_{DL}}{m_p \beta_i} \right] \Delta t - \left[ 1 - e^{-\beta_i \Delta t} \right] \left[ -v_i + \frac{F_g}{m_p \beta_i} + \frac{F_{LO}}{m_p \beta_i} + \frac{F_{DL}}{m_p \beta_i} \right] \beta_i
\]

\[
\beta_i = \frac{18 \mu}{\rho_p d_p^2}
\]

\[
\Delta t = \frac{\rho_p d_p^2}{18 \mu}
\]
When the particles are adsorbed to the channel wall, the channel diameter will change. The new algorithm of channel diameter is:

\[
\frac{1}{r_{ij,new}^4} = \frac{1}{r_{ij}^4} + 0.75 \sum_{i=1}^{N} \frac{r_p}{L_p} \left[ 1 - \left( \frac{r_p}{r_{ij}} \right)^2 \right]^2 \cdot K_1
\]

\[
K_1 = \frac{1 + 2 \left( \frac{r_p}{r_{ij}} \right)^2 - 0.202 \left( \frac{r_p}{r_{ij}} \right)^6}{1 - 2.1 \frac{r_p}{r_{ij}} + 2.09 \left( \frac{r_p}{r_{ij}} \right)^3 - 1.71 \left( \frac{r_p}{r_{ij}} \right)^5 + 0.73 \left( \frac{r_p}{r_{ij}} \right)^6}
\]

4. Results and analysis

4.1. Parameter setting

The values of filter material diameter and channel diameter in the model directly determine the concentration and purification effect of suspended solids and oil. This paper is based on the actual structural parameters of a sewage treatment plant in Daqing Oilfield and the actual measurement of laboratory samples. The range of filter material (quartz sand) size is 0.2mm, 0.4mm, 0.8mm. In each diameter of the filter material, it will be divided into many layers, filter material ratio and channel diameter range is shown in ‘Table 1’. The range of oil particle size is 25 μm–45 μm, and suspended solids particle size is 1 μm-150 μm. The concentration of oil is 25 mg / L, and suspended solids is 35mg / L, and other parameters are shown in ‘Table 2’. Simulink is used to build the simulation model and design the GUI.

| Diameter -1 | Height, m | Diameter of filter material, m | Minimum diameter of channel, m | Maximum diameter of channel, m |
|-------------|-----------|---------------------------------|-------------------------------|-------------------------------|
| Diameter -2 | 0.8       | 0.0008                           | 1.23×10⁻⁴                    | 3.312×10⁻⁴                   |
| Diameter -3 | 0.4       | 0.0004                           | 6.188×10⁻⁵                   | 1.656×10⁻⁴                   |
| Diameter -3 | 0.2       | 0.0002                           | 3.094×10⁻⁵                   | 8.28×10⁻⁵                    |

| Parameter                 | Parameter value | Parameter | Parameter value |
|---------------------------|-----------------|-----------|-----------------|
| Average mass of particles, mₚ, (g) | 8.87×10⁻⁸ | Channel surface potential, φ₂, (mV) | -29 |
| Dielectric constant of water, εₘ, (F/m) | 78.3 | Hamaker constant, H_{pwc}, (J) | 2.35×10⁻¹⁵ |
| Dielectric constant of vacuum, ε₀, (F/m) | 0.8854 | Viscosity of sewage, μ, (–) | 10.04×10⁻⁴ |
| Surface potential of particles, φ₁, (mV) | -97 | Boltzmann constant, k, /m | 2.8×10⁻⁸ |

4.2. Simulation and analysis

According to the above data, the Simulink level-2 simulation model is established. The simulation time is 5 hours, and the filtration rate ‘v’ is 0.0846m/s. The transformation curve of particle size distribution of suspended solids before and after filtration is shown in ‘Figure 4’.
Figure 4. Particle size distribution of suspended solids before and after filtration

Distribution and proportion of suspended solids before and after filtration:

Table 3. Particle size distribution ratio before and after filtration

| Particle diameter(μm) | Proportion before filtration(%) | Proportion of simulated filter (%) | Particle size distribution measurements(%) | Relative error(%) |
|-----------------------|---------------------------------|----------------------------------|------------------------------------------|------------------|
| 0-1                   | 3.93                            | 7.14                             | 7.67                                     | 7.4              |
| 1-2                   | 7.3                             | 12.1                             | 13.24                                    | 8.6              |
| 2-5                   | 12.08                           | 43.35                            | 44.71                                    | 3                |
| 5-10                  | 26.60                           | 32.88                            | 29.88                                    | -10              |
| 10-20                 | 13.37                           | 3.02                             | 3.29                                     | 8.2              |
| 20-30                 | 10.78                           | 0.98                             | 1.74                                     | 43               |
| 30-50                 | 11.31                           | 0                                | 0                                        | 0                |
| 50-100                | 14.27                           | 0                                | 0                                        | 0                |
| >100                  | 0.36                            | 0                                | 0                                        | 0                |

The mean value of particle size is transformed into:

Table 4. Mean particle size before and after filtration

| Mean particle size before filtration | Mean particle size after filtration |
|-------------------------------------|-------------------------------------|
| 24.836μm                            | 5.428μm                             |

It can be seen that after filtration, the change of particle size of suspended solids is very obvious. In ‘Table 3’, before filtration the particle size distribution is mainly concentrated in the range of 2-50 μm, and after filtration, the particle size distribution is mainly concentrated in the range of 2-10 μm. In ‘Table 4’, the mean particle size changes from 24.836μm to 5.428μm, which is an important reference to measure the quality of filtration. Compared with the actual measured value, it can be seen from ‘Table 3’, there is a certain error between the real value and the simulation value, which is due to the neglect of the interaction between particles in this model. In the actual filtering process, the interaction between particles will have a certain impact on the filtering effect. Within the allowable error range, the model can reflect the transformation of particle size distribution with time.

The conversion curves of suspended solids concentration and oil concentration before and after filtration are shown in ‘Figure 5’ and ‘Figure 6’ respectively, and the simulation values are compared with the measured values:
In the simulation process, the motion of 3196000 particles in the model is calculated. Among them, 20640000 suspended particles are adsorbed after the suspended solid filtration, and the overall filtration efficiency is about 64.6%. Finally, as can be seen in ‘Figure 5’, the average concentration of suspended solid after filtration is about 6.3 mg/L, in ‘Figure 6’, the average concentration after filtration of oil is about 4.5 mg/L.

It can be seen from the above two figures that the measured data and simulation data of suspended solids and oil have the same transformation trend. The effluent concentration increases rapidly at the beginning of filtration, and then increases slowly. There is a slight difference between the measured value and the simulated value. There are two reasons for the error: 1. Without considering the interaction between particles, the interaction between particles will have a certain impact on the effluent concentration; 2. With the filtration process and the change of filter bed structure, the filtration rate may change, and the value of filtration rate is set as a fixed value in the model. It can be seen from the calculation results that the filtration of oil and suspended solids based on the network model can really reflect the real filtration status of oilfield oily wastewater, and the numerical method reveals the filtration mechanism.
5. Conclusion
The treatment effect of oilfield oily wastewater is directly related to the quality of reinjected groundwater, and affects the oilfield exploitation and environmental protection. Improving the calculation accuracy of numerical simulation of filtration system has great practical value in the simulation of purified water system. In this paper, the trajectory tracking method is used to analysis the force and displacement of the particles in the filter channel to determine whether they are adsorbed, and the filtration efficiency and concentration are calculated by the number of adsorbed particles. The simulation results show that the model can reflect the real filtration status of oilfield oily wastewater and reveal the filtration mechanism. The simulation can help the in-depth analysis of the field and predict the sewage purification effect, which makes a certain contribution to the accurate establishment of the mathematical model of oily sewage filtration, and also provides a certain theoretical basis for seeking efficient, green and intelligent oilfield sewage treatment.

6. Appendices

- \( m_p \): Mass of particles, g
- \( \rho_p \): Concentration of particles, g/m³
- \( \rho \): Water concentration, kg/m³
- \( g \): Acceleration of gravity, m/s²
- \( \varepsilon_0 \): Dielectric constant of vacuum, --
- \( \varepsilon_m \): Dielectric constant of water, --
- \( d_p \): Diameter of particles, m
- \( r \): Distance between particles and channel surface, m
- \( \varphi_1 \): Particle surface potential, mV
- \( \varphi_2 \): Channel surface potential, mV
- \( k \): Boltzmann constant
- \( H_{pwc} \): Hamaker constant
- \( \tau_{ij} \): Channel diameter between nodes I and j
- \( L_p \): Length of channel

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