Study on oil and suspension solid removal from oil field wasted water by sedimentation

Yan Wang\textsuperscript{1,a}, Baihan Cao\textsuperscript{2,b}, Sam Reifsnyder\textsuperscript{3,c}, Sheng Gao\textsuperscript{4,d}, Diego Rosso\textsuperscript{5,e}

\textsuperscript{1}Mechanical Science and Engineering Institute of Northeast petroleum university, Daqing, China
\textsuperscript{2}Mechanical Science and Engineering Institute of Northeast petroleum university, Daqing, China
\textsuperscript{3}Department of Civil and Environmental Engineering, University of California, California, USA
\textsuperscript{4}Mechanical Science and Engineering Institute of Northeast petroleum university, Daqing, China
\textsuperscript{5}Department of Civil and Environmental Engineering, University of California, California, USA
\textsuperscript{a}Email: jwx02@126.com, \textsuperscript{d}Email: gaosheng_china@126.com

Abstract. In order to remove oil and suspended solid in oilfield wastewater, Takacs model was improved and applied to the simulation of oil floating, the parameters of oil coagulation velocity were added. By this model, the accurate oil floating model and sludge sedimentation model were established. On the basis of this model, the experimental verification was carried out by the sample from the wasted water station. By the response surface method, the influence of flow rate, treatment fluid concentration and settling time and their interaction on oil removal rate and suspension removal rate were studied, and the important influence of time factor was determined. According to the pollution degree of oil field wasted water, based on the theory and experimental method of this paper, the treatment capacity and settling time of oil field wasted water could be optimized, which provides theoretical guidance for the improvement of settlement device and the industrial application in the oilfield.

1. Introduction

The oilfield has entered the late stage of development with medium and high water cut, which has gradually increased the proportion of various pollutants in the produced fluid. The content of slop oil and suspended solids are the two most important evaluation indicators for the effect of oilfield water treatment. The high oil content in sewage will affect the normal use of water quality stabilizers and prevent the oxygen in the air from dissolving in the water. If the produced water containing slop oil and large suspended solids is directly reinjected, it will not only cause environmental pollution, but also cause blockage of rock gaps, which directly affects the exploitation of oil fields \cite{1}. Conventional water treatment methods are divided into physical methods (gravity sedimentation) and chemical methods (chemical flocculation). The physical sedimentation will remove 90\% of the oil and 70\% of the suspended solids in the oily sewage \cite{2}, which is an essential purification link for sewage treatment.
Since physical settlement is affected by factors such as water quality and process structure and so on, optimizing process parameters is an important guarantee for economic operation. The simulated response surface method can directly and effectively solve the optimization problem of efficiency and cost in settlement. At present, most researches mainly focus on the optimization and improvement of system technology by means of numerical simulation and flow field experiment [3-6]. The study found that the treatment capacity, treatment solution concentration and settling time are the most important process parameters. In order to remove oil and suspended solids from oily sewage efficiently and energy-savingly, this paper applies the Takacs model to the simulation of oil floating, increases the oil condensation speed parameter, and establishes a complete oil floating model and sludge settlement model. The simulated response surface method is used to deeply understand the physical sedimentation mechanism of oil and suspended solids, master the purification rules, optimize the process parameters of sedimentation purification, design experiments and determine the treatment capacity, treatment solution concentration and sedimentation time under the optimal conditions. It is expected to provide theoretical guidance for the improvement of settlement devices, the prediction of purification effects and the application in oilfield sewage analysis.

2. Mathematical Model
Settlement is the primary link in the treatment of oily sewage in oil fields, and the core is gravity settlement [7]. Due to the particularity of oil in oilfield sewage, the sedimentation of suspended solids and the oil floating occur simultaneously, and the sedimentation and floatation proceed independently and interfere with each other. Therefore, a mathematical model of oil floating is established, and the coupling between substances and layers are considered. Sequentially, it is necessary to describe the sedimentation process and effects of oily wastewater as a whole.

As shown in Figure 1. According to experience and actual settling system conditions, the settlement tank is divided into ten layers. The third layer is the inlet layer, and the first, seventh, and tenth layers are the oil-receiving layer, the water outlet layer, and the sludge layer. The water flow speed can be calculated according to the flow rate and the cross-sectional area of the settlement tank. After the sewage flows in, it flows upward and downward respectively. For any layer, while receiving the suspended solids from the upper layer and the rising oil from the next layer, the suspended solids in this layer also settle to the next layer, and the oil rises to the upper layer. This close coupling relationship between layers can be described by the diffusion flux $J$ of each layer, which is a function of the concentration and speed of each substance [8-12].

![Figure 1 Discretization mathematical model of settlement system](image)

2.1. Suspended solids sedimentation model
Define each flow rate shown in Figure 1, $Q_{in}$-inlet flow rate, $Q_{rec}$-de-oil flow rate, $Q_{eff}$-outflow flow rate, $Q_{w}$-sludge flow rate, $Q_{in} = Q_{rec} + Q_{eff} + Q_{w}$. The solid deposition caused by the action of water flow is equal to the product of concentration $x$ and the flow velocity $v_{b}$, $J_{b} = x_{b} \cdot v_{b}$, the solid deposition caused by
gravity is equal to the product of concentration $x$ and the solid settling velocity $v_s$. The mathematical expression of settling velocity $v_s$ is shown in equation (1) \cite{13,14}. The first term of the equation reflects the settling velocity of particles that flocculate quickly and quickly, and the second term reflects the settling velocity of particles that flocculate slowly and slowly.

$$v_{s,i} = v_0 \cdot e^{-x_i \cdot 0} - v_0 \cdot e^{-x_i \cdot v_s} \quad (0 \leq v_{s,i} \leq v_0) \quad (1)$$

Assumption

$$\frac{dm}{dt} = Q_{in} \cdot X_{in} - Q_{up} \cdot X_i - Q_{down} \cdot X_i \pm G_{up} \pm G_{down} \quad (2)$$

The formula $\frac{dm}{dt}$ is called the accumulation rate, which is the differential of the quality over time. $G_{up}$, $G_{down}$ are the upward accumulation rate and the downward accumulation rate (The unit is g/s), $Q_{up}$, $Q_{down}$ are the upward and downward flow of the layer, $i$ is Layer number.

According to $\frac{dm}{dt} = \frac{d(X \cdot V)}{dt}$, $X$ is the concentration and $V$ is the volume of the settling tank, which can be obtained:

$$\frac{d(X \cdot V)}{dt} = \frac{d(X)}{dt} \cdot V + \frac{d(V)}{dt} \cdot X \quad (3)$$

$V$ is a constant, $\frac{d(V) \cdot X}{dt} = 0$ is constant, there are:

$$\frac{d(X \cdot V)}{dt} = \frac{d(X)}{dt} \cdot V \quad (4)$$

Putting $V=A \times h$ into the above formula, the simultaneous formula (2-2), we get:

$$\frac{d(X_i)}{dt} = \left( \frac{Q_{in}}{A} \cdot X_{in} - (v_{up} + v_{down}) \right) \cdot X_i \pm J_{up} \pm J_{down} \quad (5)$$

Finally, the mathematical model of suspended solids in oily sewage is established as follows:

Oil-receiving layer (1)

$$\frac{dX_i}{dt} = \frac{(X_{i+1} - X_i)}{h} \cdot v_{up} - J_{S,i+1} \quad (6)$$

Upper level of water inlet (2)

$$\frac{dX_i}{dt} = \frac{(X_{i+1} - X_i)}{h} \cdot v_{up} - J_{S,i+1} \quad (7)$$

Water inlet layer (3)

$$\frac{dX_i}{dt} = \frac{(X_{i+1} - X_i)}{h} \cdot v_{up} + v_{down}$$

$$\cdot X_i - J_{S,i+1} + J_{S,i-1} \quad (8)$$
Lower level of water inlet (4-6)
\[
\frac{dX_i}{dt} = \left((X_{i-1} - X_i) \cdot v_{bdown} + J_{S_{i+1}} + J_{S_{i-1}}\right) / h
\]  
(9)

Water outlet layer (7)
\[
\frac{dX_i}{dt} = \left(- \frac{Q_{eff}}{A} \cdot X_i + (X_{i-1} - X_i) \cdot v_{bdown} - J_{S_{i+1}} + J_{S_{i-1}}\right) / h
\]  
(10)

Lower layer of water outlet (8-9)
\[
\frac{dX_i}{dt} = \left((X_{i-1} - X_i) \cdot v_{bdown} + J_{S_{i+1}} + J_{S_{i-1}}\right) / h
\]  
(11)

Sludge layer (10)
\[
\frac{dX_i}{dt} = \left((X_{i-1} - X_i) \cdot v_{bdown} + J_{S_{i+1}} + J_{S_{i-1}}\right) / h
\]  
(12)

2.2. Oil floating model

The purification process of the oil is just the opposite of the gravity sedimentation of the suspended solids. It is in a floating state and is also polymerizable. During the floating process, oil droplets of various particle diameters continuously collide and merge, thereby continuously changing their floating particle diameters, resulting in changes in the floating speed and diffusion flux. Therefore, an accurate mathematical model must be established to describe the movement law and coupling characteristics of the oil.

Because the similar principles of floating and settling, this paper still uses the Takacs model as the basis of the oil floating simulation, and improves it, adding the oil accumulation velocity \( v_c \), and introducing the oil accumulation flux \( J_c \), as shown in equation (13). The first term in the formula reflects the aggregation speed of the oil droplets with larger and faster aggregation in the particles, and the second term reflects the aggregation speed of the oil droplets with smaller and slow aggregation in the particles. The overall model of oil floating is obtained, and the mathematical formula is shown in (2-14)-(2-20). It can be seen from the formula that the oil floating model of each layer includes not only the mass floating flux \( J_s \) of the oil itself, but also the oil accumulation flux \( J_c \). At this time, \( J_s \) is still used to describe the coupling relationship between the layers due to flotage, and \( J_c \) is used to describe the coupling relationship between the layers caused by the accumulation of oil.

\[
\begin{align*}
V_{c,j} & = v_{c,max} \cdot e^{\frac{-e_-}{X_j} - v_0} \cdot e^{\frac{-e_+}{X_j}} \cdot J_{c,j} = v_{c,j} \cdot X_j \\
J_{c,j} & = v_{c,j} \cdot X_j \\
\end{align*}
\]  
(13)

Oil-receiving layer (1)
\[
\frac{dX_i}{dt} = \left((X_{i+1} - X_i) \cdot v_{bup} + J_{S_{i+1}} + J_{C_{i+1}}\right) / h
\]  
(14)

Upper level of water inlet (2)
\[
\frac{dX_i}{dt} = \left((X_{i+1} - X_i) \cdot v_{bup} + J_{S_{i+1}}\right) / h
\]  
(15)
Water inlet layer (3)

$$\frac{dX_i}{dt} = \left( \frac{Q_m}{A} \cdot X_{in} - (v_{wp} + v_{down}) \cdot X_i \right) + J_{s_{i+1}} - J_{s_{i-1}} + J_{c_{i+1}} - J_{c_{i-1}} \right) / h$$

(16)

Lower level of water inlet (4-6)

$$\frac{dX_i}{dt} = \left( (X_{i-1} - X_i) \cdot v_{down} + J_{s_{i+1}} - J_{s_{i-1}} + J_{c_{i+1}} - J_{c_{i-1}} \right) / h$$

(17)

Water outlet layer (7)

$$\frac{dX_i}{dt} = \left( \frac{Q_{eff}}{A} \cdot X_i + (X_{i-1} + X_i) \cdot v_{down} \right) + J_{s_{i+1}} - J_{s_{i-1}} + J_{c_{i+1}} - J_{c_{i-1}} \right) / h$$

(18)

Lower layer of water outlet (8-9)

$$\frac{dX_i}{dt} = \left( (X_{i-1} - X_i) \cdot v_{down} + J_{s_{i+1}} - J_{s_{i-1}} + J_{c_{i+1}} - J_{c_{i-1}} \right) / h$$

(19)

Sludge layer (10)

$$\frac{dX_i}{dt} = \left( (X_{i-1} - X_i) \cdot v_{down} \right) + J_{s_{i+1}} - J_{s_{i-1}} + J_{c_{i+1}} - J_{c_{i-1}} \right) / h$$

(20)

3. Analysis of Multi-factor Experiment Results

3.1. Model validation

The values of the minimum settling velocity and maximum floating velocity in the model directly determine the concentration and purification effect of suspended solids and oil, which are closely related to the physical and chemical properties of the research object. This article is based on the actual structural parameters of a sewage treatment plant in Daqing Oilfield and the actual measurement of laboratory samples. The maximum solid sedimentation rate is 321 m/day; the maximum oil floating rate is 298 m/day; the sample slop oil content is 194g/m³, the suspended matter content is 216g/m³, and the other organic matter content is 406g/m³. Simulink is used to establish a simulation model, and perform GUI design and simulation. The simulation results are shown in Table I

Table I shows the relative error between the calculated values of suspended solids and oil in each layer and the actual measured values. The maximum calculated errors of suspended solids and oil are 3.11% and 10.73%, indicating that the Takacs model is applied to the simulation of oil floating. The established oil floating model and sludge settlement model can accurately and reliably fit the actual settlement of simulated sewage.

Table II shows the relative error between the calculated value of oil and suspended solids removal rate after settlement and the actual measured value. The decreasing rate and de-suspension rate of the settling system finally reached 89.4% and 68.1%, and the simulation error of the actual value control within 1.5%. This numerical simulation analysis method can reflect the true settlement of oily sewage in the oil field, reveal the settlement mechanism, and the simulation effect of suspended solids is slightly better than that of oil.

| Layer | Suspended solids (g/m³) | Suspended solids measurement (g/m³) | Relative error (%) | Oil (g/m³) | Oil measured value (g/m³) | Relative error (%) |
|-------|-------------------------|-----------------------------------|-------------------|------------|--------------------------|-------------------|
| 1     | 16.1                    | 15.6                              | -3.11             | 444.2      | 403.9                    | -9.07             |
| 2     | 30.4                    | 28.5                              | -6.25             | 83.8       | 81.5                     | -2.74             |
| 3     | 68.0                    | 67.9                              | -0.15             | 82.4       | 76.3                     | -7.40             |
| 4     | 68.1                    | 68.2                              | 0.15              | 48.0       | 50.8                     | 5.83              |
| 5     | 68.2                    | 68.7                              | 0.73              | 39.3       | 41.2                     | 4.83              |
Table II Oil removal rate and suspended solids removal rate

|                  | Simulation value | Actual value | Deviation rate |
|------------------|------------------|--------------|----------------|
| Degreasing rate  | 89.4%            | 90.6%        | -1.34%         |
| De-suspension rate| 68.1%            | 68.8%        | -1.03%         |

3.2. Multi-factor response analysis
The biggest advantage of the response surface method is that it can use the three-dimensional curved surface graph and contour line fitted by the model to determine the corresponding relation between the evaluation index and the independent variable, which is more intuitive.

Figure 2 The influence of concentration and treatment capacity on oil removal and suspension

Figure 2 is a three-dimensional curved surface diagram showing the effect of concentration and treatment capacity on degreasing and de-suspending for a purification time of 4 hours. It can be shown from Figure 2 (a) that under the condition that the treatment solution concentration is constant, the suspended solids content continues to increase with the increase of the treatment capacity. The larger the flow, the greater the slope of the curve, and the slope can be considered as the de-suspension rate. It reflects the effect of sewage treatment. Obviously, the high flow rate of de-suspension is slightly lower, under the same treatment capacity, the treatment solution with low concentration will have higher water quality after treatment, the slope of the curve is small, and the de-suspension rate will be lower. When the processing capacity reaches a certain amount, the sedimentation system will lose the physical sedimentation situation that we believe to be steady, and of course it will also lose the role of sedimentation purification. Obviously, the treatment capacity is an important factor that affects the treatment effect. According to the size of the settling tank, ensure that the water flow speed is within 1000m³/h.

Figure 2 (b) shows that under the condition that the concentration of the treated liquid is constant, as long as there is enough sedimentation time, the increase in the treatment capacity reduces the water quality after treatment, but the overall effect on the degreasing effect in the sewage is not significant. Under the same treatment capacity, the lower the water quality, the better the degreasing effect of sewage, but the oil concentration of sewage will increase after treatment.
Figure 3 The effect of treatment volume and time on oil removal and suspension

Figure 3 is a three-dimensional curved surface diagram of the effect of treatment capacity and time on de-suspension and degreasing when the sludge oil content and suspended matter content in the sewage are both 16g/m³, which reflects the relative treatment capacity. Time on de-suspension and degreasing, the effect of the effect is very significant, and there is a certain interactive influence between the two independent variables. Figure 3 (a) shows that when the treatment time is constant, the suspended solids content increases with the increase in the treatment capacity. Under different treatment times, the longer the treatment time, the better the treatment effect, but the gap becomes smaller and smaller. When treatment time reaches 4h, the curve basically maintains a stable position, and the time factor will basically have no effect on the treated water quality. It is reflected from the side that the time factor is the prerequisite to guarantee the treatment effect. To achieve a better oil removal effect, a certain treatment time must be guaranteed.

Figure 3 (b) shows that under the condition of the same treatment time, the oil content in the sewage increases after the treatment capacity increases, but the overall effect on the degreasing effect of the sewage is not significant. The longer the treatment time is under the same treatment capacity, the better the degreasing effect of sewage is, the oil concentration of sewage will increase after treatment.

Figure 4 The influence of concentration and treatment time on oil removal and suspension

Figure 4 is a three-dimensional curved surface diagram of the sewage concentration and time on de-suspension and degreasing when the treatment capacity is 5000m³/d, reflecting that the sewage concentration has a weaker effect on de-suspension and degreasing than time. The longer the treatment time, the better the treatment effect, the oil content gradually decreases, and finally reaches a constant value. The greater the sewage concentration, the smaller the slope of the curve and the worse the water quality after purification, but the higher the de-suspension rate and the degreasing rate. The slopes of the curves are slightly different, indicating that the concentration has little effect on sedimentation.

In summary, it can be seen from Figures 2 to 4 that time is the most critical factor affecting de-suspension and degreasing. On the basis of the guaranteed time, the concentration has a weak effect on the sedimentation effect, the treatment capacity is second. The concentration has a greater impact on the de-suspension effect than the degreasing effect. As long as sufficient time is ensured, the concentration and the treatment capacity have little effect on the oil purification effect. The primary and secondary relationship of the three factors in the sedimentation purification process is: sedimentation time>concentration>treatment volume.
4. Conclusion
In order to save energy and reduce consumption and maximize the potential of physical sedimentation of oily sewage, using mathematical modeling and simulation technology, this paper introduces the Takacs model to the oil floating model, increases the oil condensation speed parameter, and establishes an accurate oil floating model and sludge settlement model. The response surface method was used to design the sedimentation treatment experiment, and the variance analysis and multi-factor analysis of interaction were carried out. It was found that the significance of the influencing factors was as follows: purification time> sewage concentration> treatment volume. The optimal treatment time of the commonly used settlement tanks in oil fields is given. The improved and complete Takacs model can accurately and reliably predict the purification effect of simulated sewage and oil field sewage. This provides on-site basic data and theoretical guidance for the search for efficient and low-consumption operation methods and the processing and analysis of dirty oil and suspended solids in the petrochemical industry.

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Reference
[1] XIE WEIHONG, ZHANG WEIZHI, JU JINGYI, et al. Analysis on technical and economic reasonable value of suspended solid content index of oilfield water injection[J]. Petroleum Planning & Engineering, 2018,29(03):9-12+52.
[2] JIN SHENGNAN. Discussion on the method of water quality improvement at the settlement node of oily wastewater treatment system[J]. Chemical Enterprise Management, 2018(35).
[3] LI XINGXING. Study on internal structure optimization of coagulation sedimentation tank[D]. ShanDong: China University of Petroleum, 2014.
[4] HAN HAICANG, SHEN LONGSHE, SUN WEI, et al. Flow field simulation of different opening ways of liquid distribution pipe in settling tank[J]. China Petroleum Machinery, 2010,38(05):45-48.
[5] DONG YANGYANG, CHEN JINGYI. Separation principle and movement analysis of oil-water sedimentation in vertical sedimentation tank[J]. Chemical Management, 2016(23):85.
[6] SUN DONGFANG. Research on Separation Characteristics and structure optimization of vertical settling tank[D]. Heilongjiang: Northeast Petroleum University, 2016.
[7] DONG LILIN. Structural Calculation and Analysis of Coagulation Settling Tanks in Oil Produced Water Treatment[J]. Oil-Gas field Surface Engineering, 2017,36(04):32-35.
[8] I. TAKÁCS, PATRY G G, NOLASCO D. A dynamic model of the clarification-thickening process[J]. Water Research, 1991, 25(10):1263-1271.
[9] LI BEN, STENSTROM M K. Research advances and challenges in one-dimensional modeling of secondary settling tanks--a critical review. [J]. Water research, 2014, 65.
[10] PATRY G. G. AND TAKFICS I. Simulator-based modelling of waste water treatment plants[J]. In Proceedings Annual Conference and 1st Biennial Environmental Specialty Conference CSCE, Vol. I, pp. 1990, 491-505.
[11] Bu' rger, R., Diehl, S., Faras, S., Nopens, I. On reliable and unreliable numerical methods for the simulation of secondary settling tank. 2012
[12] Ramin, E., Flores-Alsina, X., Sin, G., Gernaey, K.V., Jeppsson, U.,Mikkelsen, P.S., Plosz, B.G. Influence of selecting secondary settling tank sub-models on the calibration of WWTP models e a global sensitivity analysis using BSM2. Chem. 2014, Eng. J. 241, 28e34.
[13] VESILIND A. P. Discussion of"Evaluation of activated sludge thickening theories"[J], Am. Soc. cir. Engrs 94,1968,185-191.
[14] Vesilind A. P. Discussion of"Evaluation of activated sludge thickening theories", by R. I. Dick and B. B.Ewing. J. sanit. Engng Div. Am. Soc. cir. Engrs 1968,94,185-191