

NUMERICAL SIMULATION OF PARTICLE SEPARATION IN AN OIL-SAND SEPARATOR

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ABSTRACT: The gathering systems of crude oil are greatly endangered by the fine sand and soil in oil. Up to now, how to separate sand from the viscid oil is still a technical problem for oil production home or abroad. Recently, Institute of Mechanics in Chinese Academy of Sciences has developed a new type of oil-sand separator, which has been applied successfully in oil field in situ. In this paper, the numerical method of vortex-stream function is used to predict the liquid-solid separating course and the efficiency for this oil-sand separator. Results show that the viscosity and particle diameter have much influence on the particle motion. The calculating separating efficiency is compared with that of experiment and indicates that this method can be used to model the complex two-phase flow in the separator.

KEY WORDS: two-phase flow, particle separation, separator, numerical simulation

NOTATIONS

- A Area of inlet, m^2
 a Centrifugal acceleration, m^2/s
 i Grid of axial direction
 m_l Maximum grid number of radial direction
 Q Fluid mass rate, m^3/s
 R_c Maximum radius of cyclone, m
 Re Reynolds number
 r Dimensionless radial distance
 t Dimensionless time
 u Dimensionless axial velocity
 v Dimensionless radial velocity
 v_o Inlet velocity, m/s
 w Dimensionless tangential velocity
 z Dimensionless axial distance

Greek letters

- ρ Density, kg/m^3
 μ Viscosity, $Pa \cdot s$
 ψ Dimensionless stream function
 ω Dimensionless vorticity
 Ω Dimensionless angular spin velocity

Subscript

- p Particle

0 Initial

1. INTRODUCTION

In the oil production, there are some fine sand or soil in the crude oil, which result in abrasion of pipeline transporting crude oil and the related facilities. From the viewpoint of technology of oil production, these fine sands must be separated from the crude oil. Due to the high viscosity of crude oil ($0.011.0Pa \cdot s$) and the very small particle diameter of sand (usually less than $100\mu m$), how to separate sand from the viscid oil is still a technical problem for oil production home or abroad. If this problem has been solved, the quality and yield of crude oil will be improved. This is especially important for oil from old oil fields mined many years because of its higher viscosity and sand content. In general, large canisters are applied to cleaning out sand, with which sand are carried out. Obviously, the workers are very hard and it may result in the oil loss. The carrying-out oil sand may also cause the pollution.

In order to solve the oil problem of sand separating, the researchers at the Institute of Mechanics of Chinese Academy of Sciences have used the principle of liquid-solid cyclone and developed various types of oil sand separators, which have been successfully applied in the Dagang, Huabei and Shengli oil fields. The separating efficiency attains over 80%.

The liquid solid cyclone is a kind of important equipment, which is applied widely in industry of mine, petroleum, chemical engineering and coal washer. In this cyclone, high-speed liquid is carried tangentially into the separator and solid particles are separated from liquid. In general, the medium in the liquid solid cyclone is water and fine mine materials. And the medium in our oil sand separator is crude oil and fine sand.

In order to increase the separating efficiency and

decrease minimum separating diameter, the equipment is needed to be improved and the operating condition is also needed to be optimized. If only tests are adopted to solve the problem, the work will be very difficult to be conducted because of the requirement of much time or labor and the restriction of working conditions. So in this paper, a numerical method is proposed to study oil sand separators instead of some experiments and to decrease the R and D cost. Many studies of numerical simulation of liquid solid separator have been conducted^[14] for water and mine materials. Because the oil sand separator is a new type of equipment, the report of studying this problem through numerical method has not appeared before.

In this paper, the vortex-stream function method is used to solve the motion equations of fluid. The calculating program is organized and debugged and detailed fluid velocity distributions are obtained through solving the equations. The crude oil is used as the work medium, and the effect of medium viscosity on the separating course and the efficiency are analyzed.

2. EQUIPMENT

Fig. 1 is the scheme of cyclone separator, including inlet, vortex finder and spigot^[2]. Firstly liquid solid mixture was carried tangentially into the separator from the upper circle inlet and the high velocity rotating flow is formed in it. Particles were separated from the fluid and then moved down along the cone-shaped opening in the lower part of separator, finally flowed out through the spigot. Most of particle and 510 % fluid were in the outflow and the other fluid and particle flowed out from the vortex finder. In order to simplify the boundary condition of numerical model, we suppose that fluid flows into the separator from the column-shaped boundary corresponding to the height of inlet diameter.

The dimensions of the separator are as follows:

Diameter of the cyclone:	75mm
Diameter of tangential inlet:	25mm
Diameter of the vortex finder:	25mm
Diameter of the spigot:	12.5mm
Length of the vortex finder:	50mm
Length of cylindrical section:	75mm
Included cone angle:	20°
Total length of separator:	252mm
Fluid flow rate:	1.1165 · 10 ⁻³ m ³ /s

3. DIMENSIONLESS GOVERNING EQUATIONS



Fig. 1 Scheme of cyclone separator

It is very complex to determine whether the flow in a hydrocyclone is turbulent or laminar. Recent results show that the laminar flow can continue to a very high Reynolds number^[5]. For example, in some hydrocyclone, the critical Reynolds number can attain $Re_{cr} = 2.683.56 \cdot 10^5$. In this paper, the range of the Reynolds number is listed in Table 1. Because the viscosity of crude oil attains 10-1000 times of water, the Reynolds numbers in the separator are less than the critical Reynolds number. So the flow in the oil-sand separator can be calculated as the laminar flow.

The flow field in the oil sand separator is a complex three-dimensional one. But the flow field is axial-symmetrical, $\partial/\partial\theta = 0$. So the vortex-stream function method can be used to model the flow field in the oil sand separator. And the dimensionless governing equations and parameters can be written as^[11]:

$$= \frac{\partial v}{\partial z} - \frac{\partial u}{\partial r} \quad (1)$$

$$= w \quad (2)$$

$$v = -\frac{1}{r} \frac{\partial}{\partial z} \quad u = -\frac{1}{r} \frac{\partial}{\partial r} \quad (3)$$

$$\frac{\partial}{\partial t} + \frac{\partial(u)}{\partial z} + \frac{\partial(v)}{\partial r} = \frac{1}{r^3} \frac{\partial^2}{\partial z^2} + \frac{1}{Re} \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} - \frac{1}{r^2} + \frac{\partial^2}{\partial z^2} \right) \quad (4)$$

$$\frac{\partial^2}{\partial r^2} - \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} = -r \quad (5)$$

$$\frac{\partial}{\partial t} + \frac{\partial(u)}{\partial z} + \frac{\partial(v)}{\partial r} = -\frac{v}{r} + \frac{1}{Re} \left(\frac{\partial^2}{\partial r^2} - \frac{1}{r} \frac{\partial}{\partial r} + \frac{\partial^2}{\partial z^2} \right) \quad (6)$$

Table 1 Critical Reynolds numbers for various viscosity $Re = (D_c V_{in} / \mu)$

	Water		Oil	
Viscosity($\cdot 10^{-3}$) μ , Pa \cdot S	1	10	100	1000
Reynolds number ,Re	$1.54 \cdot 10^5$	$1.54 \cdot 10^4$	$1.54 \cdot 10^3$	$1.54 \cdot 10^2$

4. INITIAL AND BOUNDARY CONDITIONS

4.1 Initial Conditions

Firstly we assign zero Initially for the parameters in the flow field:

$$\begin{aligned} u &= 0 & v &= 0 & w &= 0 \\ &= 0 & &= 0 & &= 0 \end{aligned} \quad (7)$$

The velocity components at the inlet are:

$$u = 0 \quad v = \frac{Q}{S} \quad w = \frac{Q}{A} \quad (8)$$

where Q is the flow rate of inflow , S is the equivalent peripheral area of the inlet and A is the section area of inlet.

4.2 Boundary Conditions

The boundary conditions include those at the inlet , outlet , gas-liquid interface and wall.

For the inlet :

stream function :

$${}_{i+1, m_1} = {}_{i, m_1} - v_{i, m_1} r_{i, m_1} z \quad (9)$$

vorticity :

$${}_{i, m_1} = 0 \quad (10)$$

angular spin velocity :

$${}_{i, m_1} = r_{i, m_1} w_{i, m_1} \quad (11)$$

For outlet :

$$\begin{aligned} \frac{\partial^2 u}{\partial z^2} &= 0 & v &= 0 & \frac{\partial^2 w}{\partial z^2} &= 0 \\ \frac{\partial^2}{\partial z^2} &= 0 & \frac{\partial}{\partial z} &= 0 \end{aligned} \quad (12)$$

For the gas-liquid interface :

$$\begin{aligned} \frac{\partial^2 u}{\partial r^2} &= 0 & v &= 0 & \frac{\partial^2 w}{\partial r^2} &= 0 \\ &= 0 & \frac{\partial^2}{\partial r^2} &= 0 \end{aligned} \quad (13)$$

For the wall the flow distribution is fitted to the logarithmic law , and the other conditions are :

$$u = 0 \quad v = 0 \quad w = 0 \quad = 0 \quad \text{or} \quad \max \quad (14)$$

5. PARTICLE VELOCITY

The particle velocities are determined by the balances of various forces. In general , in the radial direction , there exist two forces on a single particle , the centrifugal force and the opposed drag. In the axial direction , there also exist two forces , the gravity and the opposed drag. In the tangential direction , the particle is not affected by the other forces obviously , so we assume the particle moves with the fluid. In the Stokes range ($Re_p < 1$) , the particle motion equation (BBO equation) is written for the radial direction as :

$$\frac{d^3}{6} \frac{d v_p}{d t} = \frac{d^3}{6} \frac{w^2}{r} - \frac{d^3}{6} \frac{w^2}{r} - 3 \mu d (v_p - v) \quad (15)$$

Through the integral for Eq. (15) , we obtain :

$$v_p = v - (v - v_{p0}) \exp(-t/r) + \frac{1}{d} (1 - \exp(-t/r)) r \quad (16)$$

where $= w^2/r$, $= d -$, $r = d^2/18\mu$.

When the centrifugal acceleration ais replaced by the gravity acceleration g , Eq. 16 can be used to calculate the particle velocity along the axial direction.

6. RESULTS

According to the above equations and boundary conditions , programs were computed and the computing grids were 81 41.

Fig. 2 shows the predicted velocity distribution in the axial , radial and tangential directions for oil medium. Due to the large length of the cyclone , the figure is not drawn up with the geometry scale and a small vertical grid stands for 15mm , and a horizontal grid for 10mm. The special quantities for size and velocity were specified as $R_c = 37.5$ mm (the radius of the cyclone) and $v_0 = 2.28$ m/s (the inlet velocity). With increasing the viscosity of crude oil (e. g. , from 10 to $1000 \cdot 10^{-3}$ Pa \cdot s) , the velocity distributions are

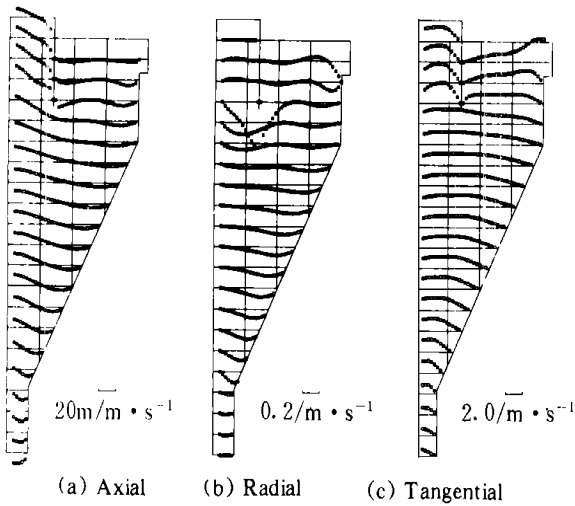


Fig. 2 Distribution of flow velocity in the separator in the axial, radial and tangential directions for oil medium ($\mu = 10 \cdot 10^{-3} \text{Pa} \cdot \text{s}$)

similar to those distributions. But the values of velocities decrease. It indicates that the viscosity of medium has much influence on the flow field. The reason of this maybe is the large viscosity of medium makes the heat dissipation and the fluid velocity reduction.

separator. It can be seen that with increasing the viscosity, particle separation becomes more and more difficult. For $\mu = 1 \cdot 10^{-3} \text{Pa} \cdot \text{s}$ (water), the particle with the diameter from 20 to $100 \mu\text{m}$ are all separated from water. And when $\mu = 1 \cdot 10^{-3} \text{Pa} \cdot \text{s}$ (crude oil), the particle with the diameter greater than $60 \mu\text{m}$ are separated. But the particle with the diameter $20 \mu\text{m}$ and $40 \mu\text{m}$ are carried by the flow up. For $\mu > 100 \cdot 10^{-3} \text{Pa} \cdot \text{s}$ (crude oil), only the particle with the diameter greater than $100 \mu\text{m}$ may be separated. From Fig. 3(c) and Fig. 3(d), we can see that the particle separating course has a little difference for two kinds of viscosity, and the course for $\mu = 1000 \cdot 10^{-3} \text{Pa} \cdot \text{s}$ will turn up earlier than that for $\mu = 100 \cdot 10^{-3} \text{Pa} \cdot \text{s}$. It shows the large viscosity prevents the particle separation from the crude oil.

Fig. 4 is the computed particle trajectories from various initial positions in the separator. The diameter of particle is $60 \mu\text{m}$ and the viscosity of oil is $10 \cdot 10^{-3} \text{Pa} \cdot \text{s}$. It can be seen that at the positions $x = 9.372 \text{mm}$ and $x = 13.125 \text{mm}$, the particle moves up with the fluid and is not separated. And at the positions $x = 16.875 \text{mm}$ and $x = 20.625 \text{mm}$, the particle is separated from the main stream. So the

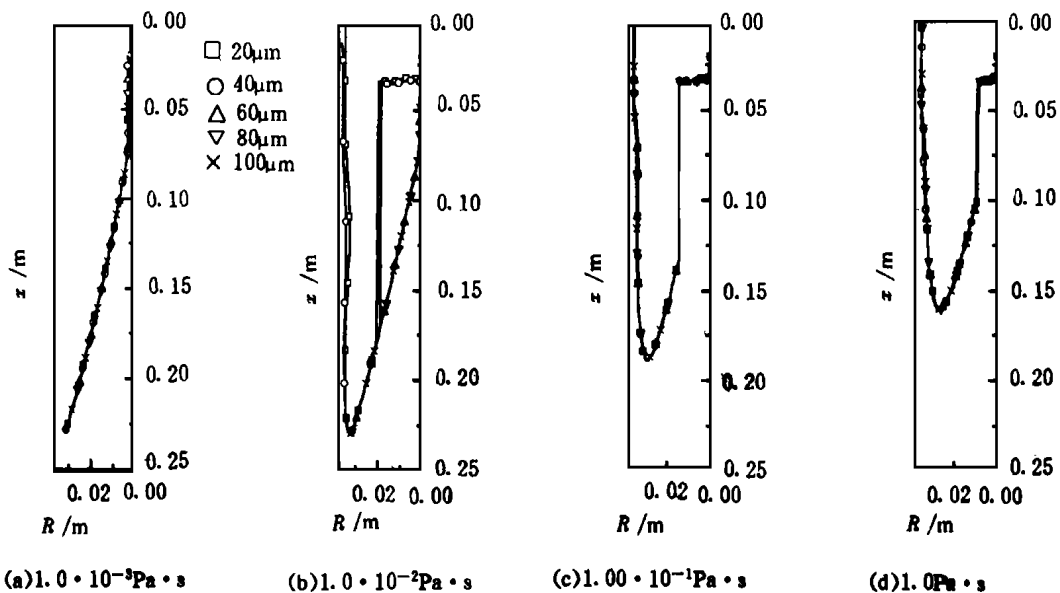


Fig. 3 Particle trajectories with various diameters in the oil-sand separator

Fig. 3 is the computed particle course with various diameters in the oil-sand separator. The viscosity of oil is $1 \cdot 10^{-3}$, $10 \cdot 10^{-3}$, $100 \cdot 10^{-3}$ and $1000 \cdot 10^{-3} \text{Pa} \cdot \text{s}$, respectively and the initial position of particle is the same as that at $x = 20.625 \text{mm}$ in the inlet of

closer to lower level of inlet the particle initial point is, the easier particle can be separated.

The sand diameter range of crude oil is very fluctuant. Table 2 shows the particle diameter distribution in a typical crude oil.

Table 2 Particle diameter distribution in a typical crude oil

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
$D/\mu\text{m}$	10	20	30	40	50	60	70	80	90	110	130	150	180	225	300	450	900
$W/\%$	0.95	4.37	6.72	5.10	7.11	5.32	2.25	4.16	2.92	1.41	12.3	38.5	3.8	1.41	1.0	1.21	1.41

Table 3 is the separating efficiency with various viscosity. It can be seen that the separating efficiency for oil is smaller than that for water. The oil viscosity is $10 \cdot 10^{-3} \text{Pa} \cdot \text{s}$. For the greater viscosity, the separating efficiency is very small. The results of experiments have been given to compare with the calculated values.

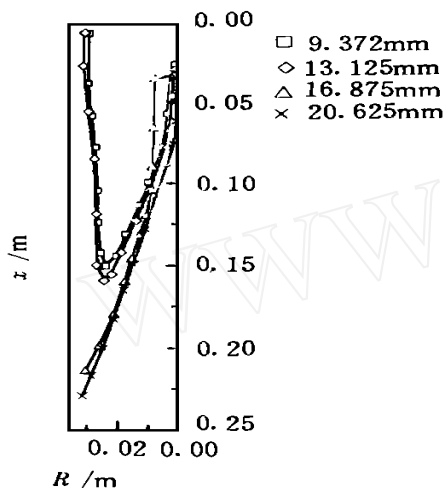


Fig. 4 Particle trajectories from various initial positions in the separator

Table 3 Separating efficiency of oil-sand separator

	Water	Oil
Calculation/ %	85.1	82.2
Experiment/ %	9095	8085

6. CONCLUSIONS

The numerical method of vortex-stream function has been applied to modeling the sand separating course and efficiency in an oil-sand separator. Results indicate

the viscosity of fluid has much influence on particle separating course. With increasing the viscosity of oil, particle separation becomes more and more difficult. The initial position also has influence on the particle trajectories. Results for separating efficiency shows that the efficiency for oil is smaller than that for water because of the greater viscosity.

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REFERENCES

1. Hsieh K. T. and Rajamani R. K., 1988: Phenomenological Model of the Hydrocyclone: Model Development and Verification for Single-Phase Flow, *International Journal of Mineral Processing*, 22, 223237.
2. Hsieh K. T. and Rajamani R. K., 1991: Mathematical Model of the Hydrocyclone Based on Physics of Fluid flow, *AIChE Journal*, 37(5), 735746.
3. Pericleous K. A., Rhodes N. and Cutting G. W., 1984: A Mathematical Model for Predicting the Flow Field in a Hydrocyclone Classifier, *Proceedings of 2nd International Conference on Hydrocyclones*, 2740.
4. Upadrashta K. R., Ketcham V. J. and Miller J. D., 1987: Tangential Velocity Profile for Pseudoplastic Power-Law Fluids in the Hydrocyclone: A Theoretical Derivation, *International Journal of Mineral Processing*, 20, 309318.
5. Xu J. R., Luo Q., 1998: *Flow Field Theory of Hydrocyclone*, Science Press, Beijing, 170186. (in Chinese).