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STUDIES ON MECHANISM OF SAND REMOVAL FROM CRUDE OIL

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ABSTRACT: Numerical simulation and experimental research on sand removal was performed. The sedimentation mechanism of sand particles of various diameters was investigated under different oil/water ratios and oil viscosities. Moreover, commercial CFD software FLUENT was applied to simulate numerically gravitational sedimenttation separation. Through the comparison between simulation and experimental results, a kind of high-efficient sand-removal method was put forward. The work was completed jointly by the Institute of Mechanics, CAS and China National Offshore Oil Corporation during the “tenth-five-year” period.

KEY WORDS: centrifugal separation, oil/sand separation, particle sedimentation

1. Introduction

At present, sand is a large threat to the daily operation in oil fields, and must be removed with the oil/gas/sand separation. In gathering/transportation system on ground, several methods, including filtering, gravitation, rotation, heating and chemical treatment, have been applied for the removal of sand. As a kind of direct and traditional separation technique, gravitational sedimentation is applied most widely in oil fields. However, this technique cannot meet the requirements of removing small-diameter sand particles as the viscosity of crude oil increases. Centrifugal separation is another popular technique used for sand removal on ground, and the requirement of removing small-diameter sand particles was met in our cooperative research. Based on theoretical analyses and experimental study, a new set of centrifugal sand-removal equipment is developed.

2. Numerical Simulation

To realize the removal of sand in oil, the sedimentation mechanism of sand particles is a key in achieving high-efficiency oil/sand separation. The commercial CFD software FLUENT is applied to numerically simulate the motion of sand particles of various diameters within liquids of different viscosities, especially gravitational sedimentation of sand particles within highly viscous crude oil, where interaction between each phase, as well as the viscosity of oil, is considered.

2.1 Fundamental equations

2.1.1 Continuity equation

The continuity equation for phase q is

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q\right) + \nabla \cdot (\alpha_q \rho_q \vec{v}_q) = \dot{m}_{pq} \qquad （1）$$

2.1.2 Momentum equation

The momentum balance for phase q is

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\alpha_q \rho_q \vec{v}_q\right) + \nabla \cdot \left(\alpha_q \rho_q \vec{v}_q \vec{v}_q\right) = \\ &- \alpha_q \nabla p + \nabla \cdot \overline{\overline{\tau}}_q + \alpha_q \rho_q \vec{g} \\ &+ \alpha_q \rho_q (\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{Vm,q}) \\ &+ \sum_{p=1}^{n} \left(K_{pq} (\vec{v}_p - \vec{v}_q) + \dot{m}_{pq} \vec{v}_{pq} \right)\end{aligned} \qquad （2）$$

where p is the pressure for all phases and $\vec{v}_{pq}$ is the interphase velocity, defined as follows. If $\dot{m}_{pq} > 0$ (*i.e.*, the mass of phase p is being transferred to phase q), $\vec{v}_{pq} = \vec{v}_p$; if $\dot{m}_{pq} < 0$ (*i.e.*, the mass of phase q is being transferred to phase p), $\vec{v}_{pq} = \vec{v}_q$. Herein, K_{pq} is the interphase momentum exchange coefficient, and depends on friction, cohesion, etc.

The momentum equation for solid phase s is

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\alpha_s \rho_s \vec{v}_s\right) + \nabla \cdot \left(\alpha_s \rho_s \vec{v}_s \vec{v}_s\right) = \\ &- \alpha_s \nabla p - \nabla p_s + \nabla \cdot \overline{\overline{\tau}}_s + \alpha_s \rho_s \vec{g} \\ &+ \alpha_s \rho_s \left(\vec{F}_s + \vec{F}_{lift,s} + \vec{F}_{Vm,s} \right) + \\ &\sum_{l=1}^{n} \left(K_{ls} \left(\vec{v}_l - \vec{v}_s \right) + \dot{m}_{ls} \vec{v}_{ls} \right)\end{aligned} \qquad （3）$$

The exchange coefficient K_{sl} between oil and sand particles can be expressed as

$$K_{sl} = \frac{\alpha_s \rho_s C_D \mathrm{Re}_s \, \alpha_l}{24 v_{r,s}^2 \tau_s} \tag{4}$$

where the relaxation time τ_s of solid particles is defined as

$$\tau_s = \frac{\rho_s d_s^2}{18\mu_l} \tag{5}$$

The drag coefficient was given by Dalla Valle[3]:

$$C_D = \left(0.63 + \frac{4.8}{\sqrt{\mathrm{Re}_s / v_{r,s}}} \right)^2 \tag{6}$$

This model is based on the measurements of the terminal velocities of particles, with correlations that are a function of the volume fraction and relative Reynolds number:

$$\mathrm{Re}_s = \frac{\rho_l d_s \left| \vec{v}_s - \vec{v}_l \right|}{\mu_l} \tag{7}$$

The exchange coefficient among sand particles can be expressed as

$$K_{ls} = \frac{3(1+e_{ls})\left(\frac{\pi}{2} + C_{fr,ls}\frac{\pi^2}{8}\right)}{2\pi\left(\rho_l d_l^3 + \rho_s d_s^3\right)} \times \alpha_s \rho_s \alpha_l \rho_l \left(d_l + d_s\right)^2 g_{o,ls} \left| \vec{v}_l - \vec{v}_s \right| \tag{8}$$

where $C_{fr,ls} = 0$ for solid particles.

2.1.3 Turbulence model

The gravitational sedimentation is relatively slow, and its velocity is less than $1.0 \times 10^{-2} m/s$. Therefore, laminar model is chosen.

2.1.4 Boundary and initial conditions

According to the characteristics of selected model, the boundary conditions are set as solid wall, namely, the adhesion conditions are given, while both the velocity and turbulent intensity are zero. Uniform mixture within the flow field is initialized at $t = 0$ and the velocity is also initialized to be zero.

2.1.5 Numerical model

Eulerian model of the Euler-Euler methods is applied to numerically simulate the separation of oil and sand particles, where the Syamlal-O'Brien [6] model is chosen to describe the interaction between phases.

3. Numerical Simulation

3.1 Numerical model

Sand particles of various diameters were mixed with a certain oil/water-ratio liquid mixture in polymethyl methacrylate tank. The height of liquid mixture is 410 mm (see Fig. 1). The diameters of tank bottom in both the model and experiment are 1 m in order to compare the numerical results and experimental data. Due to symmetry of flow field within the tank, a section in the axial direction is taken in CFD calculation, and thus the three-dimensional simulation can be simplified to a two-dimensional one. In the model, the liquid mixture is supposed to be the continuous phase as it occupies most of the space. The volume ratio of oil/sand was taken to be 10 percent, a little more than the practical value in the experiments.

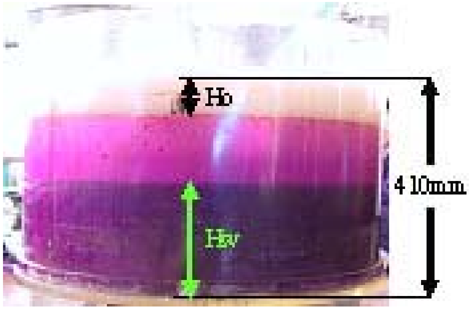

Fig. 1 Oil/Water-mixture tank

Physical properties for each phase in the model are shown in Table 1:

Table 1 Physical properties for each phase

	Oil	Sand
Density ($\mathrm{kg/m^3}$)	836	2580
Viscosity ($\mathrm{mpa \cdot s}$)	31,100,300,800	

3.2 Numerical algorithm

The commercial CFD software FLUENT is used to conduct the numerical simulation, where the SIMPLE algorithm[7] based on finite volume is applied. A P-V modified algorithm is adopted to discretize the equations.

4. Results and Analyses

4.1 Oil/sand separation and conclusions

The variation of concentration distribution with time during the sedimentation is shown in Fig 3. Time needed for sand particles of different diameters inside oil with different viscosities is also given in Table 2. As can be seen, it takes much longer time to sedimentate as the diameter of sand particles become smaller and the oil viscosity increases, and vice versa. It is very difficult for small-diameter sand particles to sedimentate in high-viscosity crude oil through gravitational sedimentation. The difference between oil/sand mixture and oil/water one is that the latter's transition layer is more uniform, which is advantageous in the separation. The smaller the diameter of sand particles is, the wider the boundary of sand particle accumulating layer will be.

Table 2 Time needed for gravitational sedimentation of oil/sand mixture

Oil viscosity mPa • s	Sedimentation time of sand particles (s)				
	20 eyes	40 eyes	60 eyes	80 eyes	100 eyes
31	33	130	310	811	1100
100	105	400	1000	2600	3400
300	310	1200	3150	7200	10800
800	840	3200	8200	19200	26400

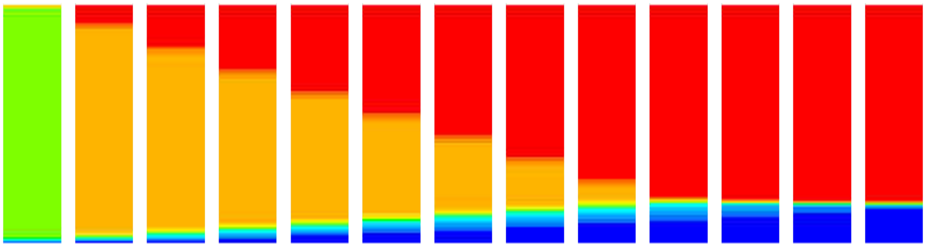

Fig. 3 Variation of sand particle concentration distribution with time

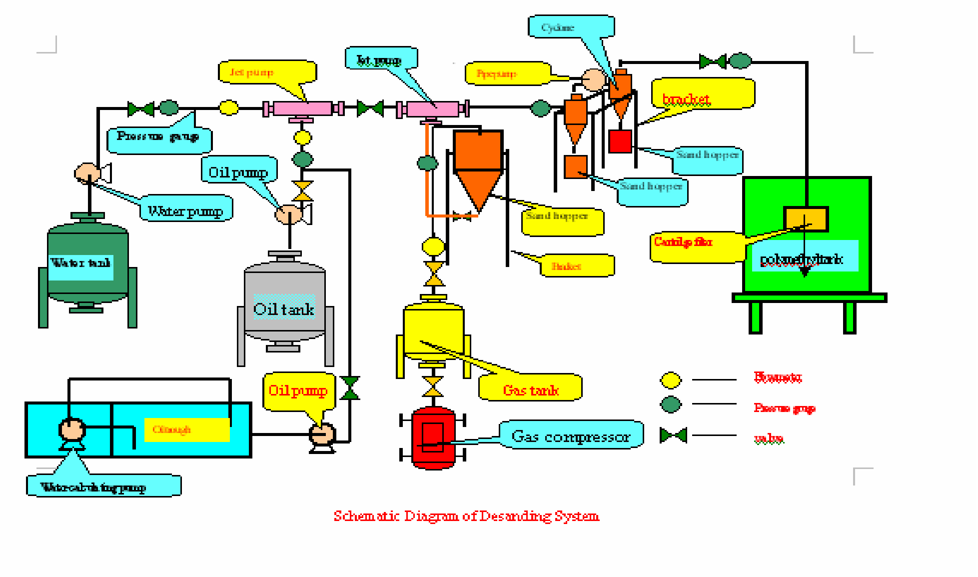

Fig. 4 Schematic diagram of desanding system

4.2 Conclusions

The following conclusions can be reached:

a. It takes more time to separate sand from oil as the oil viscosity increases and the sand particle diameters become smaller, and vice versa.

b. For small-diameter sand particles or in case of highly viscous oil, the separation efficiency of gravitational sedimentation is relatively low. Therefore, some other ways should be considered

5. Experiments

5.1 Experimental system

To achieve high-efficiency separation, some other ways should be applied besides gravitational sedimentation. It is a good idea to improve the desanding efficiency through centrifugal force. Therefore, a set of liquid/solid separation system was set up in the Institute of Mechanics, CAS, and its sketch is given in Fig. 4.

Fig. 5 Experimental system

Oil, water and sand particles are mixed using jet pump, which would be separated in two-stage cyclone separators to improve the efficiency. Three key equipments are available in the system: (I) Sand-adding device, including gas inlet pipe, water inlet pipe, sand-adding pipe, pressure gauge, valves and so on; (II) Catcher, consisting of first-stage filtering screen, second-stage screen and overflow external cylinder; (III) Separator, essential part of liquid/solid separation, where oil and solid are separated based on the principle of rotational flow. The main characteristics of such a separator are its high processing capacity and compactness.

5.2 Experimental results

The flow media include LP14 oil, water and sand particles, and the related properties are given in Table 3, and a set of typical data in Table 4.

a. Rotational separation is very valuable in improving the efficiency of oil/sand separation, where centrifugal force is the key in determining the efficiency of small-diameter sand particles.

b. For various oil viscosities, the separation efficiency of sand particles with diameters more than 100 eyes can arrive at 95 percent.

Table 3 Experimental parameters

Transient Oil Flux (m^3/h)	Transient Water Flux (m^3/h)	Total Flux (m^3/h)	Flowrate Inside Main Pipe (m/s)	Oil Pressure (Mpa)	Water Pressur (Mpa)	Air Pressure (Mpa)	Pressure at the inlet of First-stage Cyclone (Mpa)	Pressure at the inlet of Second -stage cyclone (Mpa)
6.88	4.917	11.80	2.61	0.57	0.565	0.08	0.125	0.075

Table 4 Parameters before and after separation

Particle Diameter	20-40 eyes	40-60 eyes	60-80 eyes	<80 eyes
Mass of sand particles before experiments(g)	1758.5	241.5	100	0
Separation Mass at the first-stage cyclone (g)	1503.1	320.8	72.9	23
Separation Mass at the second-stage cyclone (g)	0	10.5	72.3	39.5
Mass inside Catcher (g)	0	0	0	16
Total Separation Mass	2058.1			
Desanding Efficiency	2058.1/2100=98%			

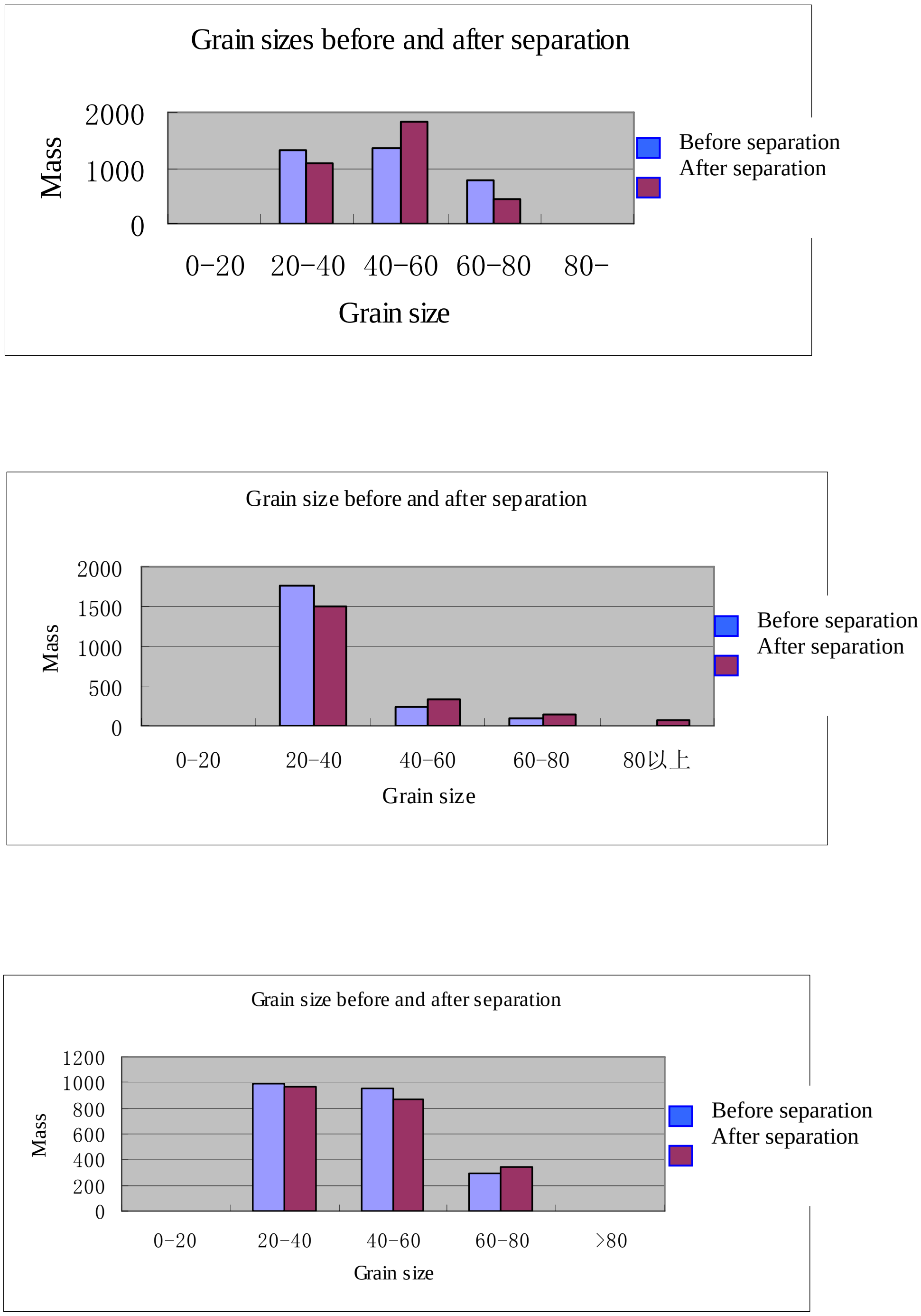

Fig. 7 Distribution of particle diameters

6. Conclusions

a. In case of highly viscous oil, the gravitational sedimentation of small-diameter sand particles becomes more difficult.

b. Centrifugal separation is an effective way in the separation of small-diameter sand particles.

c. For various oil viscosities, the separation efficiency of sand particles with diameters more than 100 eyes can reach 95 percent.

Nomenclature

g	acceleration due to gravity
α	volume fraction
ρ	density
$\vec{v}$	velocity
$\dot{m}_{pq}$	mass transfer from phase ***p*** to phase ***q***.
$\overline{\overline{\tau}}_q$	shear stress
$\vec{F}$	body force
$\vec{F}_{lift}$	lift force
$\vec{F}_{vm}$	virtual mass force
K_{pq}	interphase momentum exchange coefficient
P	pressure
$\vec{v}_{pq}$	interphase velocity
τ	particle relaxation time
d	particle diameter
n	number of phases
$v_{r,s}$	terminal velocity
e_{ls}	coefficient of restitution
$C_{fr,ls}$	——coefficient of friction between ***l*** and ***s*** solid phase
$g_{0,ls}$	——radial distribution coefficient

Subscripts

p	——liquid phase
q	——liquid phase
l	——liquid phase
s	——solid phase

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