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Technologies and Applications of Pipeline-type Oil-gas-water Separation

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Abstract: The separation of oil, gas, and water mixture is an important process in the production of crude oil. Traditional separation tanks are large, heavy, long in separation time, and high cost to manufacture. This paper introduces a separation technology with the main characteristics of the pipeline structure. This technology uses the principles of centrifugation, expansion, air flotation, and gravity separation. Pipes and other equipment are the core equipment, which has the advantages of flexible process composition, small footprint, and high separation efficiency. This technology can be used for rapid oil, gas, and water separation, solving the problems of expansion, upgrading old oilfield stations, realizing the purpose of re-injection of water in-situ, energy saving, and reducing emissions.

1. Introduction

The produced liquid from the well is usually a mixture of crude oil, natural gas, water, and other impurities. From extraction to the refinery to user use, oil-gas-water separation is the most important process in the petroleum industry. At present, most of China's onshore oilfields have entered the middle and late stage of exploitation, the moisture content of most oil wells in Daqing, Shengli, Liaohe, and other oilfields is as high as 90%, and a large part of the production cost is used for oil-gas-water separation and oily sewage treatment. To improve oil recovery, the oilfield adopts active water flooding, polymorphic oil flooding, foam flooding, ternary composite flooding, and other technologies, which makes the composition of the produced liquid more complex, and the oil-water emulsification is becoming more and more serious, which further increases the difficulty of multiphase separation. On the other hand, China's offshore oil exploitation has achieved remarkable results, with offshore oil and gas production approaching 100 million tons in 2021, accounting for more than 25% of the country's oil production. However, due to the particularity of the marine environment, there are huge differences between offshore oil exploitation and onshore oilfield output liquid treatment technology. Offshore oil exploitation requires higher and new technologies to solve the problems of large production liquid treatment, high separation index, and small space faced by offshore platform operations.

Since 2000, the scientific research institutions headed by the Institute of Mechanics of the Chinese Academy of Sciences have carried out the innovation of high-efficiency oil-gas-water separation technology through in-depth research on the multiphase flow mechanism of oil, gas, and water, put forward the concept of pipeline separation, and developed into a series of pipeline separation devices and technologies with spiral pipe, T-shaped pipe, swirl pipe, air floatation pipe, and coalescing pipe as the core, breaking through the traditional separation method based on gravity settlement of large tanks in oilfields [1,2,3].

2. Mathematical model

2.1 Two-fluid model

Both phases of oil and water can be regarded as incompressible fluids, and assuming that the two phases are in thermodynamic equilibrium, the equation for conservation of mass and the equation for conservation of momentum in the two-fluid model can be written as:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot \left(\alpha_k \rho_k \vec{u}_k\right) = 0 \quad (k = w, o) \tag{1}$$

$$\frac{\partial\left(\alpha_k \rho_k \vec{u}_k\right)}{\partial t} + \nabla \cdot \left(\alpha_k \rho_k \vec{u}_k \vec{u}_k\right) = -\alpha_k \nabla p_k + \nabla \cdot \alpha_k \tau_k + \nabla \cdot \alpha_k \tau_k^t + \alpha_k \rho_k \vec{g} - \alpha_k \rho_k \left[\vec{\Omega} \times \left(\vec{\Omega} \times \vec{r}\right) + 2\vec{\Omega} \times \vec{u}_k\right] + \vec{M}_k \tag{2}$$

In the formula, the subscript k represents the oil phase (o) and the water phase (w). If the effect of surface tension is ignored, the pressure of the phases at the interface is equal, in which case there are:

$$\vec{M}_w = -\vec{M}_o \tag{3}$$

If the discrete phase exists in the form of droplets, the interphase forces include drag, additional mass, and lift, expressed as:

$$\vec{M}_o = \vec{M}_o^d + \vec{M}_o^{vm} + \vec{M}_o^l \tag{4}$$

$$\vec{M}_o^l = C_L \alpha_o \rho_w \left(\vec{u}_w - \vec{u}_o\right) \times \left(\nabla \times \vec{u}_w\right) \tag{5}$$

$$\vec{M}_o^{vm} = C_{vm} \alpha_o \rho_w \left(\frac{D_w \vec{u}_w}{Dt} - \frac{D_o \vec{u}_o}{Dt}\right) \tag{6}$$

$$\vec{M}_o^d = \frac{3}{4} C_D \frac{\alpha_o \rho_w}{d_o} \left|\vec{u}_w - \vec{u}_o\right| \left(\vec{u}_w - \vec{u}_o\right) \tag{7}$$

$$C_D = \begin{cases} \dfrac{24\left(1 + 0.15\,\mathrm{Re}_o^{0.687}\right)}{\mathrm{Re}} & , \mathrm{Re}_o \le 1000 \\ 0.44 & , \mathrm{Re}_o > 1000 \end{cases} \tag{8}$$

In this paper, d_o is the diameter of the oil droplet and Re_o is the Reynolds number of the oil droplet.

2.2 Turbulence model

Turbulence models in multiphase flows are much more complex than single-phase flows, and the $k - \varepsilon$ model is the most widely used. For cases where the layered flow and phase density ratio are close to 1, the turbulence characteristics can be well captured by using the mixed turbulence model [2]. In the hybrid turbulence model, the equations for k and ε are:

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla \cdot (\rho_m \vec{u}_m k) = \nabla \cdot \left(\frac{\mu_{t,m}}{\sigma_k} \nabla k\right) + G_{k,m} - \rho_m \varepsilon \tag{9}$$

$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla \cdot (\rho_m \vec{u}_m \varepsilon) = \nabla \cdot \left(\frac{\mu_{t,m}}{\sigma_\varepsilon} \nabla \varepsilon\right) + \frac{\varepsilon}{k}(C_{1\varepsilon} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon) \tag{10}$$

In the above formula, the definition of mixing density ρ_m and mixing speed $\vec{u}_m$ can be written as:

$$\rho_m = \sum \alpha_k \rho_k \tag{11}$$

$$\vec{u}_m = \frac{\sum \alpha_k \rho_k \vec{u}_k}{\sum \alpha_k \rho_k} \tag{12}$$

The turbulent viscosity μ_t and turbulent flow energy $G_{k,m}$ can be expressed as:

$$\mu_{t,m} = \rho_m C_\mu \frac{k^2}{\varepsilon} \tag{13}$$

$$G_{k,m} = \mu_{t,m}\left[\nabla \vec{u}_m + \left(\nabla \vec{u}_m\right)^T\right] : \nabla \vec{u}_m \tag{14}$$

The values of each constant are the same as those of single-phase flow, i.e., Cμ=0.09, σk=1.0, σε=1.3, C1=1.44, and C2=1.92.

3. Structural model validation

3.1 Oil-water gravity sedimentation model

A 2-dimensional model is used to simulate the separation process of oil-water phases, the height of the model is 0.41 m, and the width is 1.0 m, according to the actual dimensions of the pipeline or storage tank. The physical parameters of oil and water are shown in Table 1:

Table 1. Physical properties and inlet conditions of the medium.

Medium	Density (kg·m^{-3})	Viscosity (mPa·s)	Inlet flow rate (m/s)	Phase content (%)
LP-14 White oil	836.0	31.0	1.0	0.305
Tap water	998.0	1.003	1.0	0.695

Figure 1 shows the growth curve of the oil-water mixture of oil droplets with different particle sizes over time under gravity sedimentation. The oil-water phases are gradually separated, and the thickness of the mixed layer is reduced, which is consistent with the experimental observations. The oil-water separation process at droplet diameters of 0.1 mm, 0.15 mm, 0.2 mm, and 0.25 mm was numerically simulated. Figure 1 shows the change in water layer height with time, and the results show that the water layer height increases linearly.

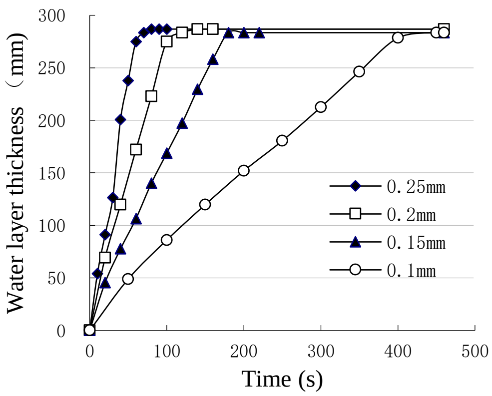

Fig.1 Calculation results of oil-water two-phase Gravity sedimentation model

3.2 T-shaped piper separation model

The T-shaped pipe consists of 2 to 3 horizontal tubes and multiple vertical tubes, which are separated by gravity and stratification as a pre-separation device for gas-liquid and liquid-liquid. When the oil-water or gas-liquid two-phase mixture flows in the horizontal pipe, the heavy phase is subjected to gravity and descends to the bottom horizontal pipe through the T-shaped bifurcation structure, and the vertical pipe converges. The light phase with less density floats up to the top horizontal pipe through the T-shaped structure and the vertical pipe, forming a two-phase layered flow. The T-shaped bifurcation structure plays the role of two-phase flow path selection, the vertical pipe serves as the channel for the dynamic exchange of flow between the two phases, and the horizontal pipe achieves the purpose of transportation and aggregation [4,5].

The separation effect is mainly determined by the design of the T-shaped pipe bifurcation structure, the diameter of horizontal, and vertical pipes, the height and number of vertical pipes, and the diversion ratio of upper and lower horizontal pipes. The early T-shaped pipe design is relatively simple, and the current T-shaped pipe has evolved a variety of structural forms according to the separation needs, such as the horizontal pipe at the top of the T-shaped pipe. The gas-liquid separation is changed to an inclined design, the vertical pipe is changed to an inclined design scheme to reduce the disturbance at the outlet, the rectifier and diversion device are added to the inlet and outlet, and the functional structure is added inside the pipeline. Figure 2 shows the color map of the distribution of the volumetric phase content of the oil phase in the three-layer T-pipe when the oil density is 900kg/m3 and the inlet oil content is 15%.

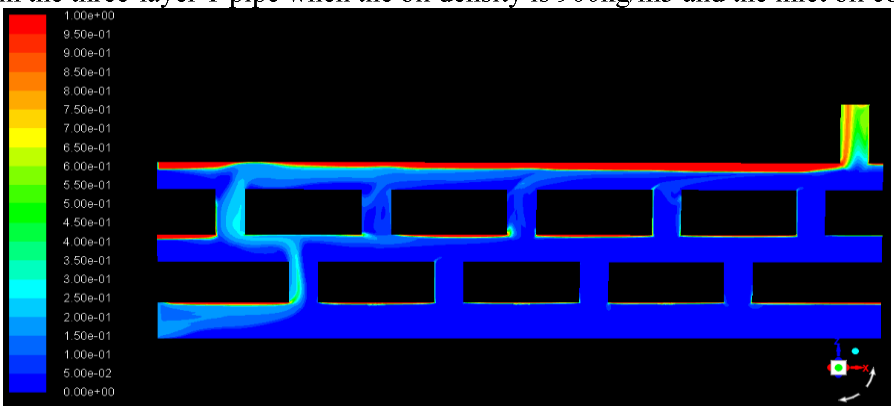

Fig. 2 T-tube separation numerical simulation of oil phase content distribution

3.3 Cyclone pipe separation model

The separation of cyclone pipe takes advantage of the density difference of the miscible medium to achieve efficient separation of different media through the motion paths generated by different centrifugal forces of the rotating flow field. According to the different rotation methods and inlet and outlet structures, the swirl tube separator can be divided into columnar cyclone separator and guide vane type cyclone separator [6,7,8].

The cylindrical cyclone rotates tangentially through the horizontal inlet, the oil-water two phases rotate and flow at high speed in the cylindrical separation section, the medium of each phase produces different centrifugal forces under the action of density difference, and the heavy phase (such as water or sand) gathers towards the pipe wall under the action of gravity and centrifugal force and spirals downward, and finally discharges from the bottom outlet; Light phases (such as oil or gas) gather in the center of the cyclone, in the opposite direction of axial motion to the heavy phase, and are finally discharged from the top outlet. The deflector-type cyclone rotates axially through the fluid, and the light phase gathers to form an oil core or gas core, which is led out through the axial outlet; The heavy mass phase is thrown towards the side wall of the pipe and is led out through the interface pipe section at the side wall. Compared with the columnar cyclone, the internal flow field of the deflector-type cyclone is symmetrical and stable, and there is no axial reverse flow; Radial dimensions can be installed horizontally, vertically or obliquely, or downscale, giving it a good advantage in downhole or size-constrained scenarios.

The results of the oil-water separation experiment of the column-type cyclone show that by controlling the mixing ratio of oil and water, the oil and water entering the cyclone can form an oil core under the action of centrifugal force. The valve that controls the top light phase outlet and the bottom-heavy phase outlet adjusts the shunt ratio (the ratio of the top outlet flow to the inlet flow), and as the split ratio increases from 0 to 0.95, the oil core can form shapes of different thicknesses and lengths.

The process and effect of oil-water separation were further studied by numerical simulation (as shown in Figure 3: red represents the oil phase, blue represents the water phase), in which the model setting conditions are: pipeline diameter 75 mm, inlet flow 10 $m^3 \cdot h^{-1}$, inlet oil content of 8%, oil viscosity 245 mPa·s, oil outlet flow of 20% of the total inlet flow, and oil phase density from 850 $kg \cdot m^{-3}$. With the increase of the density of the oil phase, the oil content of the outlet gradually increases, and the oil phase content in the formed oil core gradually decreases. Separation of oil-water phases with similar densities is more difficult.

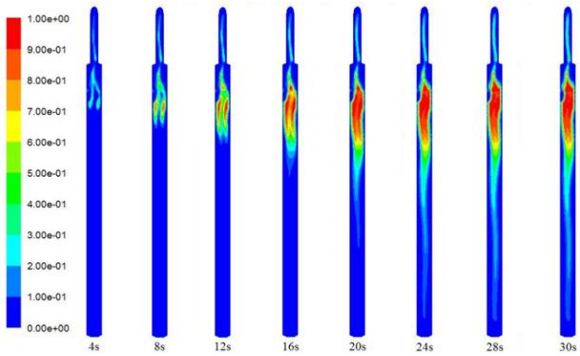

Fig.3 Cyclone pipe structure model and calculation results of oil-water two-phase separation

4. Engineering cases

After years of continuous research and improvement, pipeline separation technology has become increasingly mature, and the different pipe separation structures in this technology can be applied separately or in combination.

4.1 Treatment of oily sewage

Adopted the same structured cyclone, the separation and oil removal efficiency can be improved through a multi-stage series connection, and the equipment is connected in parallel to solve the problem of processing capacity. Swirl sewage treatment plants are already in operation with capacities from 1 to 800 m3/h per unit. There are 5 sets of equipment in parallel to treat 18000 m^3 of polymer-bearing wastewater per day in a joint station of Dagang Oilfield, the oil concentration of the inlet sewage of the equipment is 100-500 mg/l, the oil content of the outlet can be reduced to 60-80 mg/l after treatment, and the single-stage cyclone oil removal rate is greater than 75%. The experimental data is shown in Figure 4.

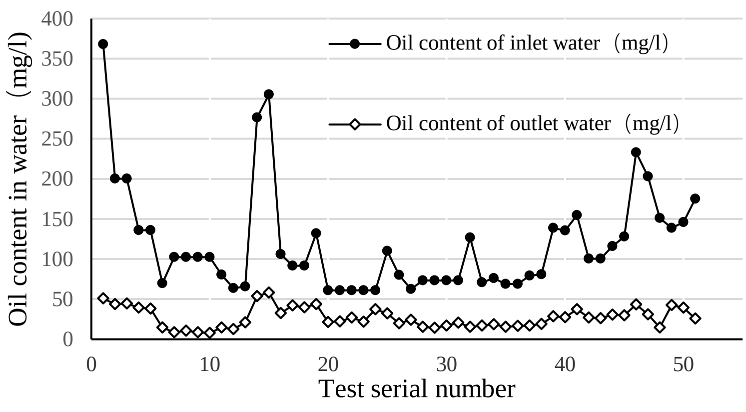

Fig. 4 Oil removal by cyclone experimental

4.2 Water separation treatment of offshore-produced liquid

Given the rapid water separation and treatment needs of offshore produced liquid in an oilfield, a three-stage cyclone treatment test device (as shown in Figure 5) is designed, the first-stage cyclone separates most of the oil and gas in the produced liquid, and the second and third stages treat the oily wastewater separated by the first stage cyclone. According to the different separation tasks, each stage cyclone adopts different specifications and parameter structures, the oil content of the sewage separated by the first stage cyclone is less than 1000mg/l, the oil content of the second stage cyclone is no more than 500mg/l, and the oil content of the third stage cyclone is below 50mg/l.

Fig. 5 Offshore platform separation equipment

4.3 Oil, gas, and water three-phase separation treatment

To realize the purpose of local water distribution and on-site reinjection of a metering and transfer station in a northwest oilfield, through the combination of multi-stage pipeline cyclone, T-pipe, pipeline coalescer, S-type pipe separator, and other structures, the rapid separation of oil, gas, and water of the oil well-produced liquid is realized. The gas is used for heating boilers, water is injected back into the ground, and oil is transported abroad. The equipment is designed to handle a capacity of 400 m^3/d and achieve a water separation of 200 m^3/d. The effluent contains ≤ 50 mg/l, and then after the two-stage sedimentation and oil removal and suspended solids removal by the water injection skid, it can be directly injected back into the ground. After removing water, the pipeline separation equipment reduces the external transmission pressure by 50%, alleviates the scaling and corrosion problems of the pipeline, and prolongs the service life of the pipeline.

5. Conclusion

Compared with traditional separation technology and equipment, pipeline separation technology has the following relative advantages in oil, gas, water, and sand separation:

1) Physical separation method based on the principle of mechanical composite, fast separation speed, high efficiency, no chemical agents, no risk of secondary pollution;
2) Compared with the traditional gravity settling tank, it can reduce the land occupation and volume by more than 40%, and the operating weight of the equipment is reduced by more than 50%, which is especially suitable for engineering construction or transformation under the condition of limited space and bearing capacity;
3) Modular process design, easy to integrate with existing processes, flexible layout, easy to move;
4) Simple and fast manufacturing and installation, can be assembled on-site, no heavy lifting equipment is required;
5) Easy operation and management, convenient maintenance, and maintenance.

Given the separation needs of two or more mixed media such as oil, gas, and water in oil and gas fields, the pipeline separation technology developed based on hydrodynamic process and simulation breaks through the traditional separation method based on gravity settlement to achieve rapid and efficient dynamic separation under pipeline flow. The pipeline separator includes a series of separation devices with the pipeline as the main structure, such as a T-shaped pipe, spiral pipe, swirl tube, and swirl air flotation separation tube, which comprehensively adopts the mechanical principles of gravity, buoyancy, centrifugal, air flotation, expansion and so on, which greatly improves the heterogeneous separation efficiency. Different separation devices can be used alone or in combination, and the combination mode is fast and flexible, which adapts to the current development needs of separation technology in the oil and gas industry and has broad application prospects. Engineering applications show that pipeline separation technology can greatly reduce the cost of oilfield production fluid treatment, show good technical and economic advantages, and have good economic and social benefits and environmental benefits.

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