Optimized Design of Oil-Water Separator for Injection and Production in the Same Well

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ABSTRACT
To realize the injection and production technology in the same well for high-water-cut oil wells, the multicup isoflux oil-water separator was optimized and designed according to the separation principle similar to multicup isoflux gas anchor. In the design process, the number of openings and apertures in each layer of the separator increased step by step from top to bottom, the liquid intake of each liquid inlet was similar, and the residence time of each produced liquid in the separator was long enough. Through the analysis of the optimal combination of different segmentation methods, the number of openings and different apertures, considering the requirements of machining, parameters such as aperture size, aperture classification and the number of openings were optimized according to the principle of fluid dynamics. While ensuring that the residence time of produced liquid in the settling cups at each part exceeds 150s, this design gives full play to the role of settling cups, effectively shortens the length of downhole oil-water separator, and saves production and operating costs.

1. INTRODUCTION

Downhole oil-water separation [1-6] (DOWS) is a new technology, which solves the problems of high oil well production and large separation workload in the development of high-water-cut oilfields, addresses the huge investment and energy loss caused by water injection, and shows remarkable economic benefits and environmental protection effects. At present, there are two basic ways of DOWS: hydrocyclone separation technology and gravity separation technology [7-12]. According to the separation principle similar to multicup isoflux gas anchor, the multicup isoflux oil-water separator was designed, which can solve the problem that the existing downhole centrifugal oil-water separator has poor separation effect and cannot be applied on a large scale.

The success of downhole oil-water separation field test fully proves the feasibility of applying downhole oil-water separation technology in oil field [13-18]. Stokes law is applied to gravity separation, that is, in the separation process, due to the density difference between oil and water, the crude oil will move upward, and the water will settle below the crude oil. The advantage of gravity separation DOWS technology is that the oil and water will be gravity separated in the oil casing circular space [19-21]. The two-stage hydrocyclone DOWS system has been tested in Venezuela. It is found that this DOWS system is only suitable for casing with large diameter. Therefore, this system has not been widely used. The advantage is that it is easier to install than any type of DOWS system.

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Through experiments, the factors affecting the separation effect of oil-water separation hydrocyclone are studied, which are summarized into three categories: size variable, operation variable and mixed liquid variable [22-25]. Three principles for the design of liquid-liquid separation hydrocyclone: first, due to the small density difference between the two liquid phases, a strong rotating centrifugal force is generated to ensure that the phase with small density can produce radial movement; Second, in order to obtain strong rotating centrifugal force and avoid excessive pressure drop, the diameter of hydrocyclone is very small, so the diameter length ratio should be large enough to ensure the necessary residence time; Third, it is necessary to ensure the stability of the fluid at the air column without fluctuation, otherwise heavy mixing will occur and the separation performance will be reduced. These three principles must be observed in the design of cyclone separator.

2. MULTICUP ISOFLUX OIL-WATER SEPARATOR

Figure 1 is a schematic diagram of multicup isoflux downhole oil-water separator. Figure 2 shows the structure of settling cup. Multiple settling cups are installed on the central tube of multicup isoflux downhole oil-water separator, and sediment bores are drilled inside the settling cups to remove solid impurities. The central tube is drilled with a liquid inlet near the bottom of inner side of each settling cup, the central tube is connected into several, and a protective body is installed between each. The central tube is the inlet channel for reinjection water, and the oil sleeve annulus is the inlet channel for produced liquid, which is connected with a plug underneath.

The separator is connected to the lower part of oil pump. The formation produced liquid first enters the settling cup, is separated into reinjection water with higher water cut and produced liquid with lower water cut, and then enters the oil pump via the liquid inlet. The flow area of liquid inlet is accurately calculated according to the maximum output during the upstroke of oil pump, so that the liquid entering the central tube of oil-water separator in each cup is approximately equal.

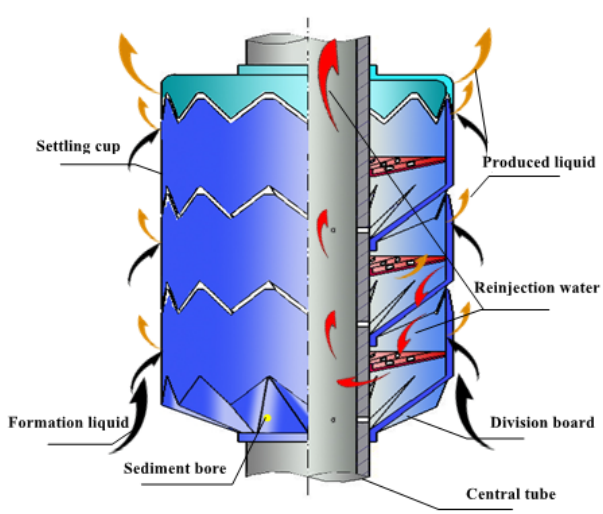

Figure 1. Multicup Isoflux Downhole Oil-Water Separator

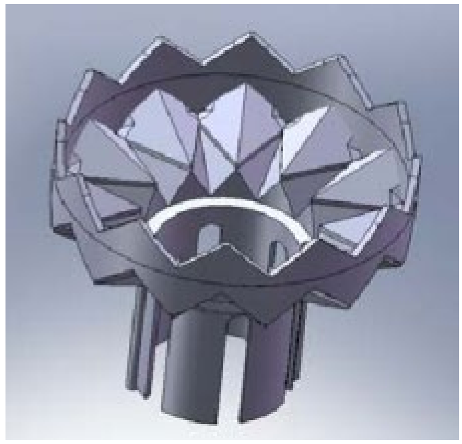

Figure 2. Structure of Settling Cup

3. FLOW EQUATION

The formation produced liquid flows through the settling cup and is naturally settled and separated through the difference of oil and water density. After separation, the reinjection water with higher water cut enters the central tube and is produced by the oil pump; The produced liquid with low water cut enters the oil sleeve annulus and is produced by the oil pump. In the entire separation process, the liquid intake of each settling cup should be approximately equal each time the oil pump sucks. To this end, the hydraulic calculation and analysis of isoflow parameter design were carried out.

(1) Friction pressure difference in the central tube:

$$\Delta p_f = \rho g h_f = 87.66 \frac{\upsilon^{0.25}}{D^{4.75}} Q^{1.75} L \tag{1}$$

where, Δp_f is the friction pressure difference in the central tube of separator, Pa; ρ is the density of produced liquid, kg/m^3; h_f is the head loss in central tube, m; Q is the daily processing capacity of separator, m^3/d; υ is the kinematic viscosity of produced liquid, m^2/s; D is the inner diameter of the central tube of separator, m; L is the length of central tube, m.

(2) Inner and outer pressure difference of central tube:

$$\Delta p = \rho g h_j = \rho g \xi_k \frac{v^2}{2g} \tag{2}$$

where, Δp is the inner and outer pressure difference of separator central tube (working pressure difference), Pa; h_j is the local head loss at the orifice, m; ξ_k is the local resistance factor; v is the flow velocity of orifice, m/s.

We assume that the flow through each orifice is q_0, the diameter d of orifice can be derived from Equation (3) as:

$$d = \sqrt{\frac{4q_0}{\pi v}} = \sqrt{20\frac{\rho q_0^2}{\Delta p \pi^2}} \tag{3}$$

The equation indicates that a working pressure difference corresponds to an aperture, and the smaller the working pressure difference, the larger the aperture, and vice versa. With smaller working pressure difference, the aperture is larger, which is more conducive to machining, and the inner and outer pressure of central tube is closer, which will produce less influence on the working condition of pump after installation of settling cups, and also helps to inhibit degassing of produced liquid in the central tube. However, if the working pressure difference is too small, the liquid intake at the upper and lower ends differs greatly. As a result, the liquid drop velocity v in the top settling cup is too large, and the gas will be carried into the central tube and the pump, resulting in the reduction of oil-water separation efficiency and pump efficiency. Therefore, a reasonable working pressure difference is the key to hydraulic design.

We assume that the working pressure difference at the bottom orifice of central tube is Δp, and the working pressure difference at the top orifice is $\Delta p_f + \Delta p$. According to the orifice flow calculation formula, the flow of each orifice at the top and bottom is shown respectively as below:

$$q_1 = \frac{\pi}{4} d^2 \sqrt{2\frac{\Delta p + \Delta p_f}{\xi_k \rho}} \tag{4}$$

$$q_n = \frac{\pi}{4} d^2 \sqrt{2\frac{\Delta p}{\xi_k \rho}} \tag{5}$$

where, q_1 is the liquid intake of the top orifice, m^3/s; q_n is the liquid intake of the bottom orifice, m^3/s.

The flow of each orifice at the top and bottom is defined as flow ratio, and let the holes in the central tube have the same diameter, then the flow ratio is

$$\alpha = \sqrt{\frac{\Delta p + \Delta p_f}{\Delta p}} \tag{6}$$

where, α is the flow ratio.

Too small working pressure difference of the settling cup will lead to too large flow ratio. In severe cases, the flow of the top orifice may be much greater than that of the bottom orifice, and the gas-liquid mixture will flow smoothly into the gas anchor central tube and pump without separation from the orifice of upper settling cup. In practical engineering design, the upper limit of flow ratio can be set as 1.05 to ensure equal flow at each orifice.

In the hydraulic design calculation, the aperture was calculated after setting a working pressure difference, and then the corresponding friction pressure difference and flow ratio were calculated. If the resulting flow ratio is greater than 1.05, the working pressure difference should be increased gradually to satisfy the flow ratio requirement; If the resulting flow ratio is less than 1.05, the working pressure difference should be reduced gradually to obtain the largest possible aperture.

4 OPTIMIZED DESIGN ANALYSIS

4.1 Structural design

Figure 3 shows the stepped flow channel model [26-29], which is made by cutting (on the central tube) stepped flow channels, narrow at the top and wide at the bottom, corresponding to the upper, middle and lower settling cups. This is to reduce the flow of upper and middle settling cups while increasing the flow of lower cup, so that the flow of upper, middle and lower settling cups is approximately equal. For this purpose, based on a dozen flow channel models with different width ratios established, numerical simulation analysis was performed for the corresponding flow field, and the stepped slotting parameters of 10:12:16 as shown in Figure 4 were finally optimized.

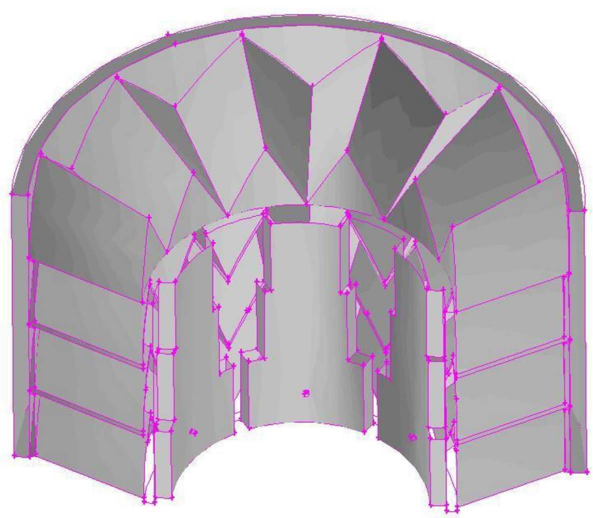

Figure 3. Stepped Flow Channel Model

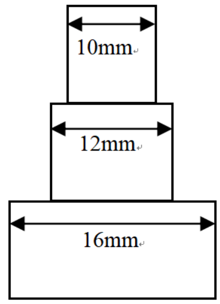

Figure 4. Stepped Channel Diagram

4.2 Numerical simulation and result analysis

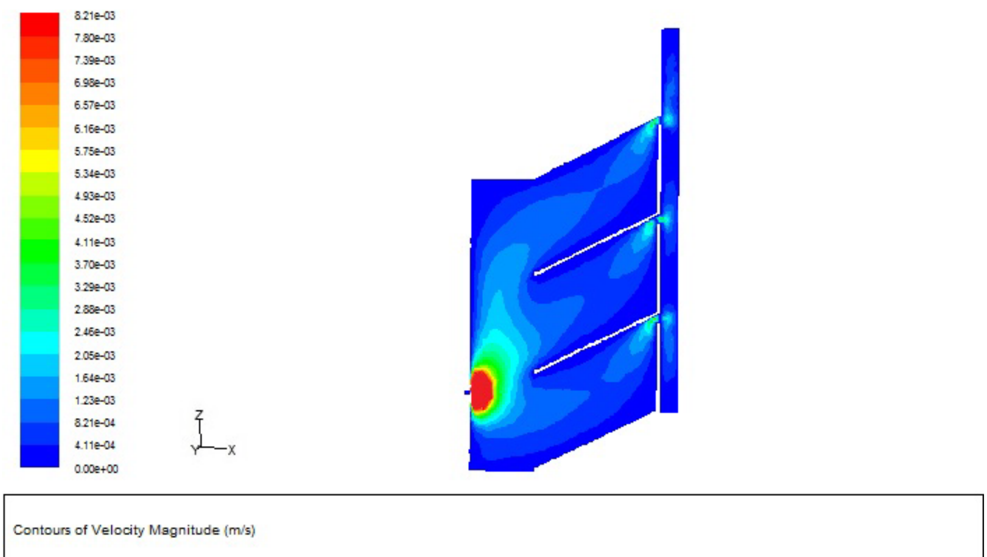

Figure 5. Velocity Image in Settling Cup

According to the model shown in Figure 3, Fluent is used for simulation, and the velocity distribution cloud diagram is shown in Figure 5 and the flow pattern diagram is shown in Figure 6. When the slotting depth is between 0 and 3mm, the flow ratio slotting depth relationship curve is calculated, as shown in Figure 7.

It is observed that the flow decreases with the increase of slotting depth. The flow ratio starts to be less than 1.05 when the slotting depth is 2mm.

The following equation was obtained by regression of the relation curve between flow rate and slotting depth in step slotting in Figure 7:

$$\alpha = 0.0355x^2 - 0.1751x + 1.2489 \quad (7)$$

where, α is the flow ratio; x is the slotting depth, mm.

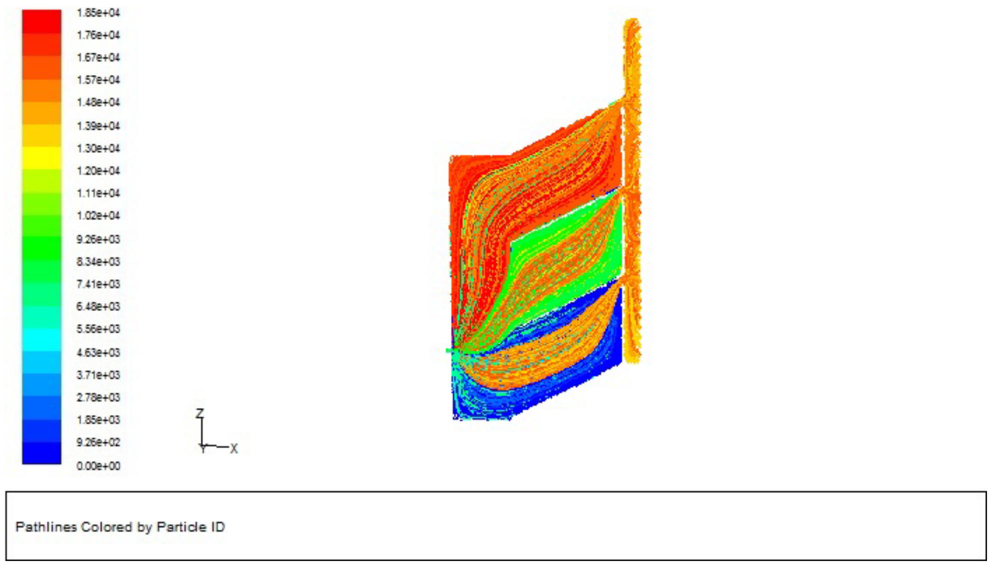

Figure 6. Upper Streamline Chart of Vertical Outlet Section in Settling Cup

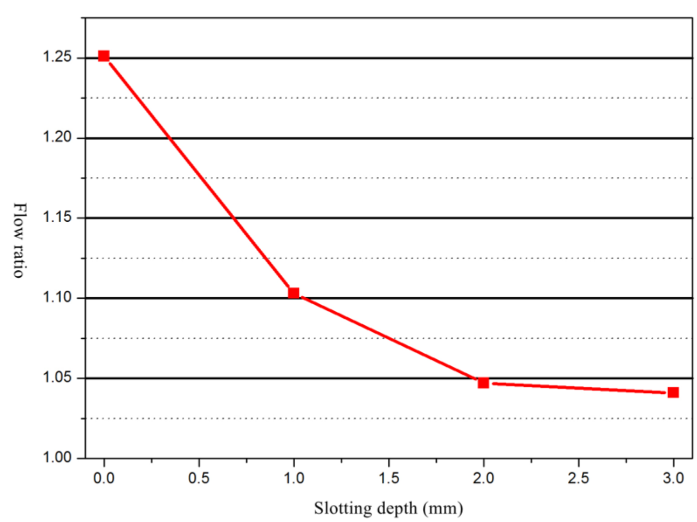

Figure 7. Flow Ratio-Slotting Depth Relation Curve

The mass flow in upper, middle, and lower cups at different slotting depths is shown in Figure 8. Apparently, the mass flow of liquid in the upper and middle cups decreases with the increase of slotting depth, while the mass flow of liquid in the lower cup increases with the increase of slotting depth.

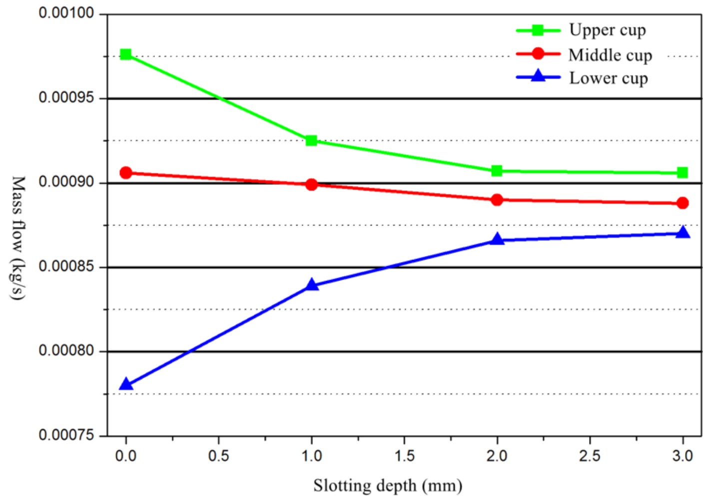

Figure 8. Variation of Mass Flow in Upper, Middle and Lower Cups with Different Slotting Depths

The stepped flow channel means increasing the flow channel of lower cup while reducing the flow channel of upper and middle cups. Besides, the use of stepped flow channel will produce local resistance at the steps, so that the flow of upper and middle cups is reduced, and the flow ratio is less than 1.05.

5. CONCLUSIONS

(1) According to the principle of fluid dynamics, the multicup isoflux oil-water separator was optimized and designed, which gives full play to the role of settling cups, effectively shortens the length of downhole oil-water separator and saves production and operating costs.

(2) The flow field of each modification scheme was numerically simulated by Fluent, and the resulting flow field parameters such as velocity distribution and pressure distribution were analyzed; Based on the laboratory test results of oil-water separator, the optimal size of stepped flow channel was finally determined.

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