Research of the Heavy Oil Mixer with Helical-jet Mode

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Abstract: The light oil is injected into the layer and mixed with heavy oil through tools, so as to achieve the purpose of viscosity reduction. Among them, the performance of mixer directly affects the viscosity reduction effect of heavy oil and the energy consumption of mining machinery. Firstly, a new type of static helical-jet mixer is proposed, which achieves mixing through the principle of "micro-porous jet & helical turbulence flow". Secondly, the CFD of mixing performance is carried out, and the key parameters such as span angle, helix angle, perforation diameter, perforation density and differential pressure between inlet and outlet to unevenness coefficient and dilution ratio is obtained. Finally, According to the working conditions of oil viscosity of 4520.90 mPa. s and pressure difference of 5.60 MPa in oil production area stratum in Tahe Oilfield, Xinjiang, a mixer for docking 3-1/2" tubing is designed to achieve an unevenness coefficient of 0.076, which is a significant improvement over the performance of conventional tailpipe-type dilution tools. The research results have laid a theoretical foundation for the on-site engineering application of the tool, and can also provide a new reference for improving the level of heavy oil dilution and mining technology.

1. Introduction

Heavy oil [1] has the characteristics of large reserves, wide distribution and poor fluidity. Mixing viscosity reduction technology [2] is an effective method to exploit underground heavy oil reservoirs. The mixer is used to inject light oil [3] or polymer flooding agent [4] into the oil layer to achieve the effect of reducing heavy oil viscosity and improving its fluidity, so as to facilitate the lifting of the oil [5]. The performance of the mixer directly affects the viscosity reduction effect of heavy oil, which is essential for improving the efficiency of heavy oil production, reducing the loss of light oil, reducing the energy consumption of oil extraction and the failure rate of mechanical equipment [6]. The mixer is divided into static, dynamic and composite structures. Typical structures include: (1) a rotating dynamic mixer consisting of continuous spiral blades [7, 8] or discontinuous blades [9] and intermediate shafts drives the blade to rotate through oil flow and continuously changes the direction of liquid flow to achieve the purpose of oil-liquid mixing with different viscosity. (2) A number of channels [10-12] are set up in the pipe wall, and the flow energy of the light oil itself is used to jet the liquid into heavy oil to achieve mixing. (3) A plurality of baffles [13] are arranged in the pipe, and holes of various shapes and angles are opened thereon. The holes in each orifice plate project substantially non-overlapping in the axial direction, causing the fluid path to achieve a helical flow for mixing. (4) Mixing chamber is formed by a series of elliptical throttle valves [14]], each of which is deflected by 90 degrees from each other, and a portion between each of the two throttle valves exhibits a tetrahedral shape. When fluid passes through these throttles, then rotational mixing occurs immediately.

Due to the different structural forms of the mixers mentioned above, there are large differences in the applicable reservoir conditions of heavy oil and the mixing effects achieved. Especially with the

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decrease of temperature in the process of oil lifting, the phenomenon of slug flow occurs and even oil pipe is blocked, resulting in an increase in the energy consumption of the pumping system and the amount of light oil. In this paper, a new type of spiral jet heavy oil mixer is proposed. The influence of various key structural parameters on its working performance is studied. Indoor mixing experiment proves that the mixer has a good mixing effect.

2. Structure and advantages of spiral-jet mixer

Figure 1 is the structure of spiral jet heavy oil mixer [15] proposed in this paper, which includes outer cylinder, wing plate, upper and lower plugs, etc. Wherein, the outer cylinder body is provided with a light oil port, and the wing plate is provided with a perforating hole, and two wing plates with an angle α and the upper and lower plugs together form a jet cavity, which is arranged at a helix angle β with the geometric centerline of outer cylinder.

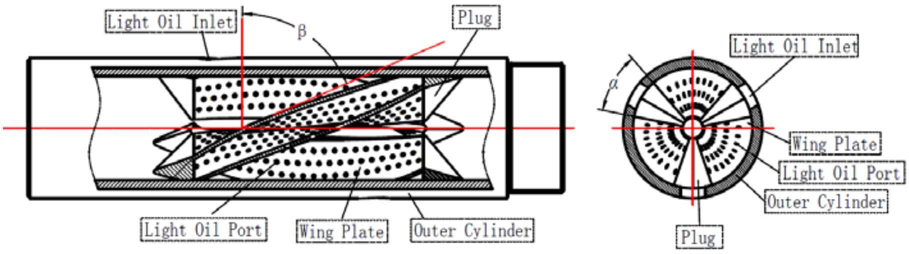


Fig.1 Structure schematic diagram of helical-jet heavy oil mixer

Heavy oil seeps into well-bore from the formation, and then enters the mixer through tail pipe, and returns to the inside of the cylinder under the action of suction force or formation pressure. light oil enters jet chamber from light oil port, enters mixing area through the perforation under the action of liquid column pressure, mixes with the heavy oil flowing there and forms a mixed oil. The oil continues to ascend and is lifted to the ground through oil pipes. The process principle is shown in Figure 2.

The main advantages of the mixer are as follows:

(1) Thickness of heavy oil is reduced by separating heavy oil into three parts (or more) through a jet chamber; At the same time, by using the fluid kinetic energy of light oil liquid, the light oil is mixed into heavy oil by jet through perforation, which can make light oil more uniformly dispersed into heavy oil and achieve the purpose of high-efficiency mixing.

(2) Jet chamber is designed as a structure with pitch angle, so that the circumferential rotation and turbulence state can be formed during the upward and backward process of heavy oil or mixed oil, which is conducive to further improving the mixing uniformity of oil.

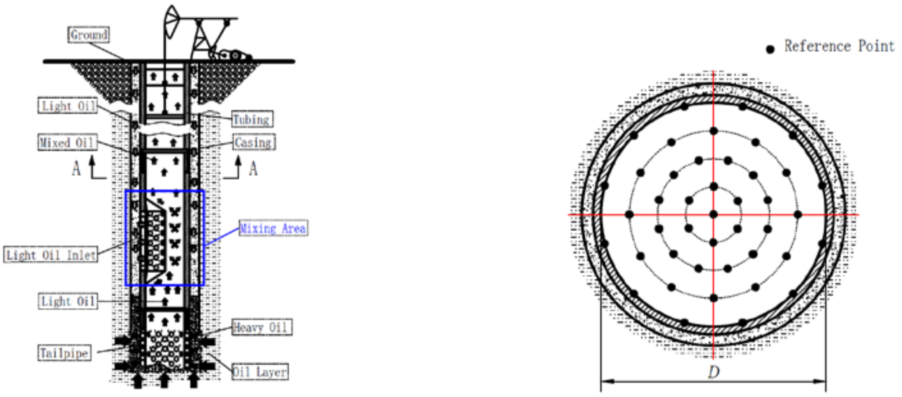
(3) The oil is mixed by means of “jet + helix”, resulting in a small pressure drop of heavy oil and high mixing efficiency. It is beneficial to reduce the energy consumption of oil lifting and reduce the failure rate of ground pumping equipment.

3. Performance simulation and structural parameter sensitivity analysis of helical-jet mixer

Through CFD (Computational Fluid Dynamics) simulation technology, the sensitivity relationship between key size parameters and mixing performance of new tools was studied, and a set of targeted optimization and evaluation methods was established with the combination of laboratory experiments.

3.1 Numerical calculation model and evaluation index of mixing performance

In the selection of CFD simulation control equations, the rotation and swirling flow of the liquid should be considered in order to better handle the flow with high strain rate and large streamline bending. RNG k-ε model [16,17] is a flow viscosity calculation model with low Reynolds number considering turbulent vortices, which can obtain higher calculation accuracy in CFD analysis for the oil mixing with different viscosity.



A-A

(a) Process principle (b) Reference points for calculating unevenness coefficient

Fig.2 Schematic diagram of the process principle of diluting viscosity with heavy oil using mixer

In order to quantitatively evaluate the mixing effect of the mixer, the unevenness coefficient [18] obtained after the simulation of the mixer is used as an evaluation index of oil mixing effect. After the two-phase oil is mixed and lifted for a certain distance, the volume fraction of the light oil of a limited reference point in the same section is taken as original parameter, and the ratio of arithmetic mean to standard deviation is the unevenness coefficient (hereinafter referred to as "coefficient"). Its expression is [19]:

$$\lambda = \frac{\sigma}{\bar{\varphi}} \tag{1}$$

Among them,

$\bar{\varphi} = \sum_{i=1}^{n} \frac{\varphi_i}{n}$, arithmetic mean;

$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\varphi_i - \bar{\varphi})^2}$, standard deviation;

n--Total number of reference points.

Among them, the selection rule of the reference point is shown in Figure 2(b). The reference point is divided into five circle layers, each of which has the same radial distance, and the reference points on the same layer are evenly distributed, for a total of 43. At the same time, under actual conditions, it is always desirable to minimize the amount of light oil under the premise of obtaining a good mixing and viscosity reduction effect. Therefore, the volume fraction (referred to as "dilution ratio") between the mixed light oil and the output mixed oil is taken as a reference index [20].

3.2 Numerical calculation scheme design

Five most important structural parameters in this tool are selected as the analysis objects: helix angle, perforation diameter, perforation density, span angle and inlet and outlet pressure difference. Here, a combined orthogonal experimental scheme is used to perform a combined calculation. Wherein, the parameters of helix angle β (β angle in Fig. 1) are 36.87°, 44.43°, 53.13°, 64.16°respectively; The perforation diameters are 4.00mm, 5.00mm, 6.25mm and 7.50mm respectively; The perforation density is defined as the ratio of the area of pore area per unit surface area, which are 0.064, 0.080, 0.100, 0.125, respectively; The span angle (α angle in Fig. 1) is 24.00°, 30.00°, 37.50°, 46.88°, respectively; The inlet and outlet pressure differences are 5.60 MPa, 7.00 MPa, 8.75 MPa, and 10.94 MPa, respectively. The selection of above calculation parameters mainly refers to the production data under the actual process conditions of heavy oil mixing and the selection of "1.25" priority series. As shown in Table 1.

Table 1 The Numerical calculation scheme and results

No.	Factor					Analysis result	
	helix angle /(°)	perforation diameter /mm	perforation density	span angle /(°)	inlet and outlet pressure difference /MPa	unevenness coefficient	dilution ratio
1	36.87	4.00	0.064	24.00	5.60	0.306	0.298
2	36.87	5.00	0.080	30.00	7.00	0.415	0.260
3	36.87	6.25	0.100	37.50	8.75	0.187	0.373
4	36.87	7.50	0.125	46.88	10.94	0.123	0.422
5	44.43	4.00	0.080	37.50	10.94	0.322	0.306
6	44.43	5.00	0.064	46.88	8.75	0.217	0.367
7	44.43	6.25	0.125	24.00	7.00	0.316	0.242
8	44.43	7.50	0.100	30.00	5.60	0.332	0.287
9	53.13	4.00	0.100	46.88	7.00	0.181	0.423
10	53.13	5.00	0.064	37.50	5.60	0.102	0.407
11	53.13	6.25	0.125	30.00	10.94	0.280	0.255
12	53.13	7.50	0.080	24.00	8.75	0.261	0.321
13	64.16	4.00	0.125	30.00	8.75	0.344	0.304
14	64.16	5.00	0.100	24.00	10.94	0.362	0.282
15	64.16	6.25	0.080	46.88	5.60	0.154	0.384
16	64.16	7.50	0.064	37.50	7.00	0.157	0.312

3.3 Performance simulation analysis of mixing tools

The type of heavy oil selected in the above calculation scheme is the test data of the indoor experiment (90 °C) of heavy oil sample in the TH1073 well in Tahe Oilfield. The light oil type is the test data of indoor experiment (50 °C) of light oil for thinning and viscosity reduction in the first plant of Tahe Oilfield [21]. See the Table below.

Table 2 Types of typical physical properties of heavy oil and light oil

Type	Viscosity/mPa.s	Density/kg/m^2	Inlet Pressure/Mpa
Heavy Oil	4 520.90	980	13.38
light oil	8.56	910	/

The computational fluid domain of the mixer is extracted from the established three-dimensional model and divided into tetrahedral meshes. The mesh quality reaches 0.3 and the number is 423 660, which can meet the requirements of computational accuracy. The result of the division is shown in Figure 3. The simulated volume fraction distribution nephogram of light oil is shown in Fig. 4.

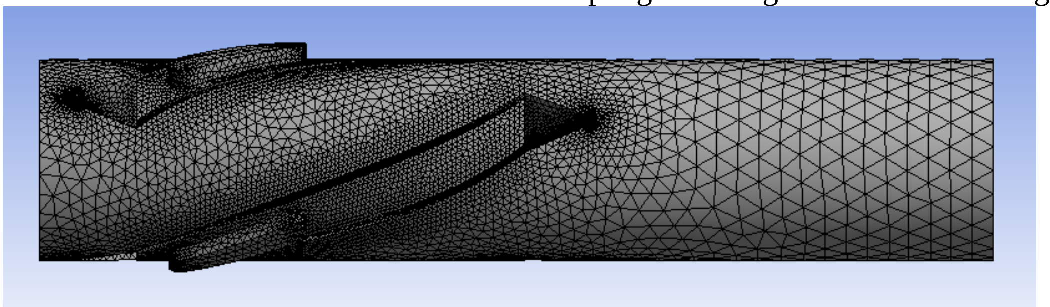


Fig.3 Grid division diagram of the helical-jet mixer

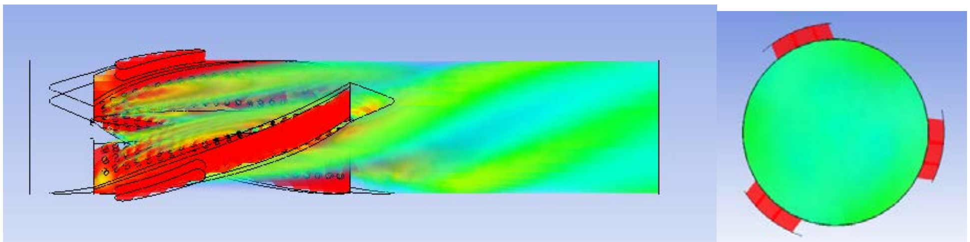


Fig.4 light oil volume fraction distribution nephogram of the mixer under mixing condition

3.4 Sensitivity analysis of structural parameters of the mixer

A range analysis is performed on the results of each data in Table 1 to determine the sensitivity relationship. Firstly, the primary and secondary order of influence of the five factors on the mixing unevenness coefficient is: span angle, perforation density, perforation diameter, helix angle and inlet and outlet pressure difference, as shown in Figure 5. Unevenness coefficient index decreases as span angle, perforation diameter and helix angle increase; it increases with the increase of perforation density and inlet and outlet pressure difference. Especially with the increase of span angle, the thickness of heavy oil flowing through the mixing area decreases, and it is easier to be penetrated by light oil, thus achieving better mixing effect. The primary and secondary order of influence on the dilution ratio is: span angle, helix angle, perforation density, inlet and outlet pressure difference and perforation diameter, as shown in Figure 6. The dilution ratio increases with the increase of span angle and helix angle, and decreases with the increase of perforation density, inlet and outlet pressure difference and perforation diameter, but the influence trend is not strong. In the mixing area, the fluidity of heavy oil is better than that of heavy oil under incomplete conditions, especially under the influence of helix angle, the dilution ratio increases obviously.

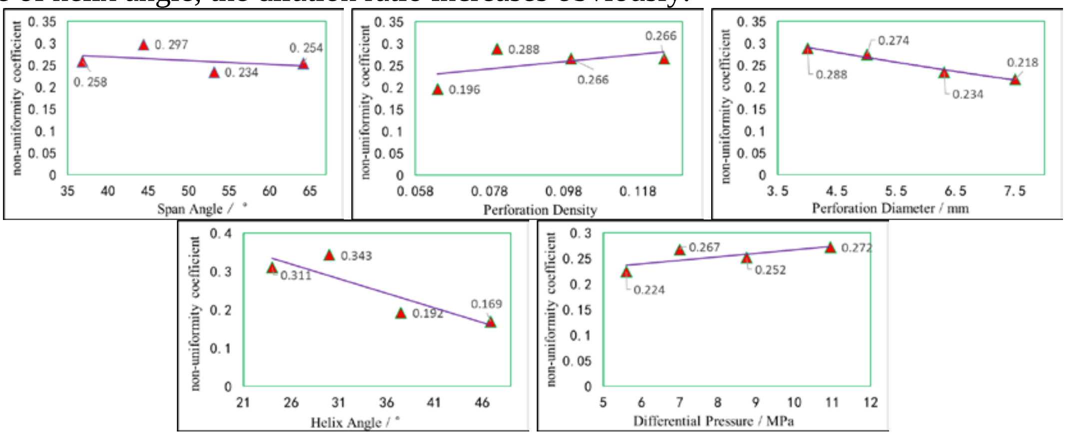


Fig.5 The Sensitivity of Structural Parameters to the non-uniformity coefficient

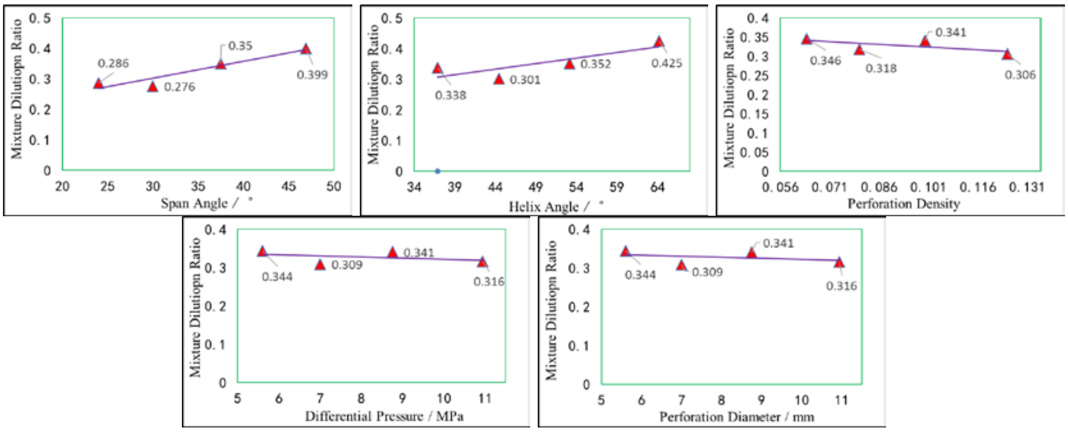


Fig.6 Sensitivity relationship of structural parameters sensitivity to dilution ratio

4. Optimization design scheme and experimental study of spiral-jet mixer

4.1 Mixer optimization design

According to the above research conclusions, and considering the influence relationship of the dilution ratio, the final optimized combination scheme is determined as follows: the span angle is 37.50°, the perforation density is 0.064, the perforation diameter is 7.5 mm, the helix angle is 53.13°, and the inlet and outlet pressure difference is 5.60 MPa. According to the above parameters, the mixer structure is redesigned. By using the same simulation analysis method, the unevenness coefficient is obtained of 0.096, which is the lowest compared with the 16 groups of simulation experiment results and achieves good viscosity reduction index.

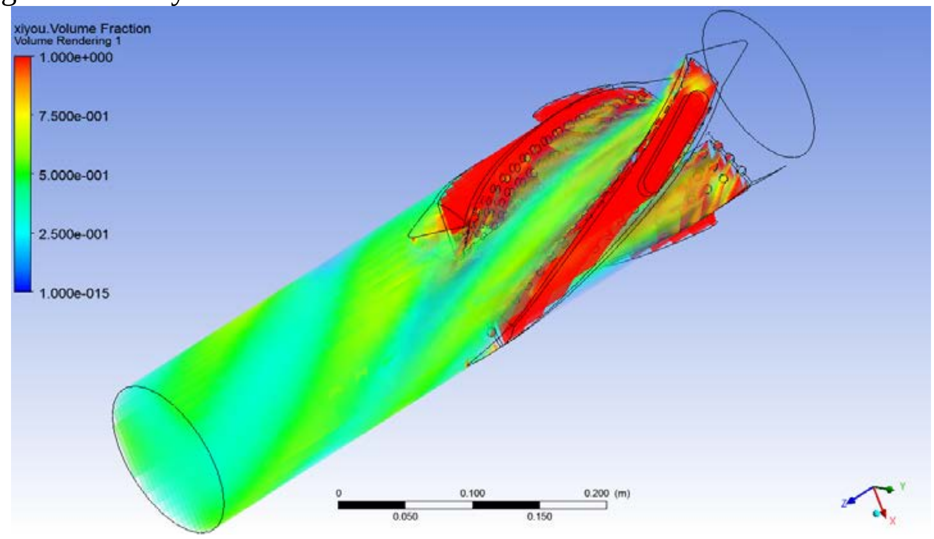
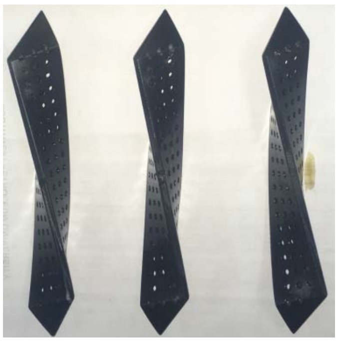


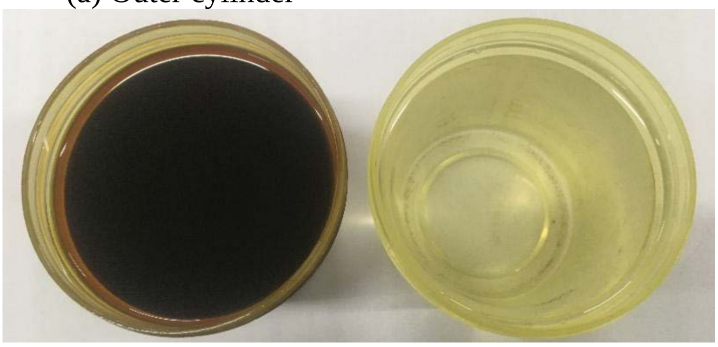
Fig.7 Mixed volume fraction nephogram of tool optimization structure scheme

4.2 Experimental analysis of working performance of mixers

According to the optimized parameter scheme, a Φ112mm spiral-jet heavy oil mixer and a tailpipe mixer experimental device are designed and manufactured to verify the technical advancement of new mixer and the correctness of the simulation analysis. Among them, the experimental heavy oil is dark gray turbine oil with a density of 910kg/m³ and a viscosity of 1 130mpa.s; The colorless light oil is mineral oil with a density of 877kg/m³ and a viscosity of 1.23mpa.s. The viscosity difference between the two is nearly 920 times, which can achieve the purpose of mixing performance detection.

(a) Outer cylinder





(b) Wing plate (c) Heavy oil (left) and light oil (right) for experiment use

Fig.8 New mixer parts and heavy oil & light oil samples used in experiments

The experimental operation process is as follows: the first is to open the mixed oil valve to the maximum, then open light oil valve and light oil pump, and adjust the relative pressure to 0.56Mpa; the second is, until the light oil fills all the cavities, to open the heavy oil valve and the heavy oil pump to maintain the relative pressure to 0.56Mpa; the third is to observe that when the entrance of the new mixer is occupied by light oil, and the color of the mixed oil at the upper pipe no longer changes significantly, start sampling at “sampling point” and record the outlet pressure gauge. The experimental principle is shown in Fig. 9. In addition, the contrast experiment is to dismantle the new mixer and lengthen the tail pipe, and then repeat the above experiment, and obtain mixed oil samples at the sampling point as contrast data. Since the indoor experiment cannot reach the actual working condition parameter, the set fluid pressure parameter value is one tenth of the actual working condition. The purpose of horizontal contrast is achieved by the experiment.

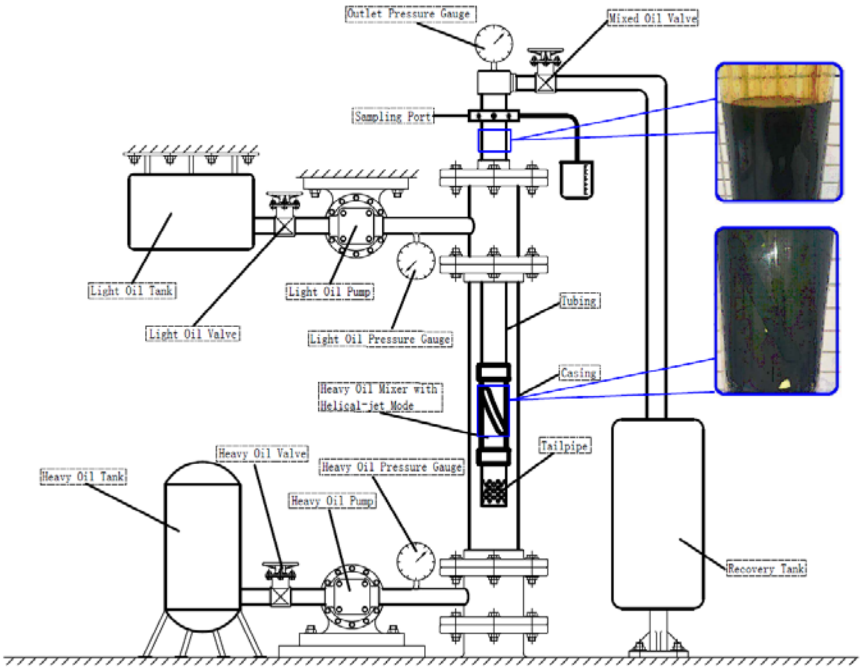
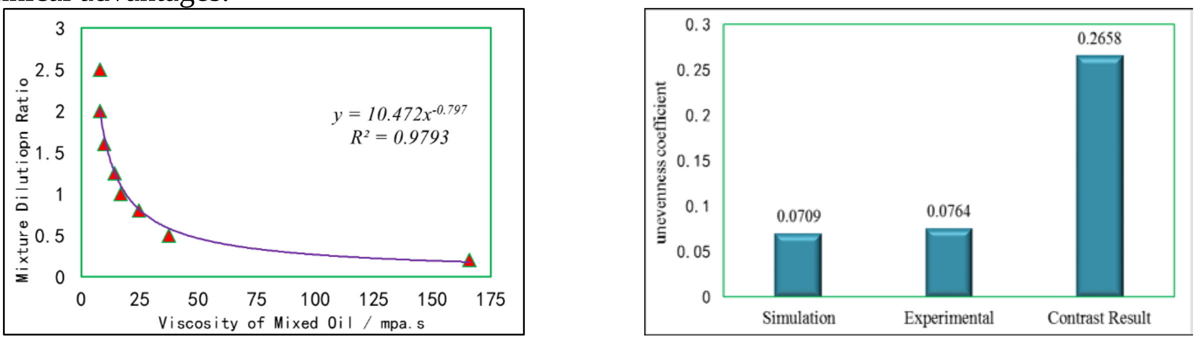


Fig.9 New experiment principle of new mixer

The experiment first needs to establish the functional relationship of “dilution ratio-oil viscosity”, and establish the relationship curve shown in Fig. 10(a) by the unit experiment of measuring the viscosity of mixed oil with different dilution ratios. Based on the above relationship curve, the viscosity of the sampled mixed oil is measured, and the dilution ratio data of each sampling point is obtained by conversion, which is used as the basis for calculating the oil blending unevenness coefficient. As shown in Fig. 10(b), the measured unevenness coefficient is 0.076, and the CFD simulation result under the same conditions is 0.071, and the relative error is 7.76%. The contrast result of the traditional tail pipe dilution experiment under the same conditions is 0.266, which indicates that the mixing effect of the spiral-jet heavy oil mixer is greatly enhanced, and has obvious technical advantages.



(a) (b)

Fig.10 Comparative analysis of experimental results and simulation results

5. Conclusion

(1) This paper proposes a new type of spiral-jet heavy oil mixer, which includes a jet cavity composed of an outer cylinder, a wing plate and a plug. The jet cavity is disposed on the inner wall of the outer cylinder and is spirally distributed, which divides the inner space of the outer cylinder into a plurality of regions. The turbulent flow caused by the oil flow of the light oil and the spiral return of

the oil liquid can be used to achieve the purpose of thick oil mixing. The tool has the advantages of simple structure, small pressure drop of heavy oil and high mixing efficiency.

(2) For the “unevenness coefficient” evaluation index of the mixer, the primary and secondary factors of the sensitivity of the structural parameters to the index are: span angle, perforation density, perforation diameter and helix angle. In particular, with the limited increase in span angle and perforation diameter, the limited reduction in perforation density can effectively improve the mixing performance of the tool.

(3) For the “dilution ratio” evaluation index, the primary and secondary factors of the sensitivity of its structural parameters are: span angle, helix angle, perforation density and perforation diameter. The trend is that the amount of light oil increases significantly with the increase of the span angle and helix angle; with the increase of perforation density and perforation diameter, it decreases.

(4) A Φ112mm spiral-jet heavy oil mixer is designed for the actual working conditions of heavy oil mixing in Tahe Oilfield in Xinjiang. The tool has a span angle of 37.50°, a helix angle of 53.13°, a perforation diameter of 7.50 mm, and a perforation density of 0.064. Through simulation analysis, the tool can obtain an unevenness coefficient of 0.096 with a dilution ratio of 0.401.

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