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RESEARCH ARTICLE - PETROLEUM ENGINEERING

A Novel Hydraulic Tool for Lost Circulation Control While Drilling with Improved Plugging Effectiveness

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Abstract Lost circulation is one of the most troublesome and costly problems encountered in drilling. This problem is magnified while drilling in deeper, depleted and complex reservoirs. Based on the nation of preventive treatment, the paper intends to present a novel hydraulic tool with a purpose of lost circulation control while drilling. The hydraulic energy of swirling jet is employed in this tool to push the granules in drilling fluid into the fractures, and "an artificial borehole wall" is formed to enhance the pressure-bearing capacity of leakage formation. Moreover, a computing model for flow rate allocation of the tool is developed. The result of comparison experiment on plugging effectiveness manifests that plugging effectiveness with the use of hydraulic tool is much better than that without the tool. The maximal pressure-bearing capacity of experimental core is increased to 8.3 MPa under the experimental circumstances, which demonstrates that the hydraulic tool can provide an effective preventive treatment for lost circulation. Furthermore, field tests of the hydraulic tool are conducted in deep wells and depleted reservoirs. The statistical results validate that the plugging effectiveness can be improved greatly by employing the tool, and the pressure-bearing capacity of formation in depleted reservoir is increased to 11.6 MPa.

Keywords Hydraulic tool · Lost circulation control while drilling · Plugging effectiveness · Pressure-bearing capacity

Abbreviations

LCM	Lost circulation material
WSM	Well-strengthening material
BHA	Bottom hole assembly
ROP	Rate of penetration
RFT	Repeat formation test

List of symbols

Q_s	Flow rate of rig pump (L/s)
Q_b	Flow rate of drill bit (L/s)
Q_c	Flow rate of swirling jet nozzles (L/s)
I	Flow rate ratio
p_b	Pressure drop of drill bit and hydraulic tool (MPa)
p_s	Rig pump pressure (MPa)
K_L	Circulating pressure loss coefficient
L	Well depth (m)
ξ	Coefficient of local resistance
γ	Unit weight of drilling fluid (N/m^3)
v_e	Equivalent jet velocity of drill bit nozzles and swirling jet nozzles (m/s)
g	Acceleration of gravity (N/kg)
C	Discharge coefficient of nozzle
d_e	Equivalent diameter of drill bit nozzles and swirling jet nozzles (cm)
A_0	Total equivalent area of nozzles (cm^2)
ρ_w	Density of drilling fluid (g/cm^3)
d_{ej}	Equivalent diameter of bit nozzles (cm)
d_f	Equivalent diameter of hydraulic energy distribution device (cm)
d_c	Equivalent diameter of swirling jet nozzles (cm)

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v_c	Jet velocity of swirling jet nozzle (m/s)
p_c	Pressure drop of hydraulic tool (MPa)
v_j	Jet velocity of drill bit nozzles (m/s)
F_j	Impact force of drill bit jet (kN)
N_{bj}	Hydraulic horsepower of drill bit (kW)
F_c	Impact force of swirling jet (kN)
N_c	Hydraulic horsepower of hydraulic tool (kW)
v_{pc}	The ROP (m/h)
n	Rotation speed of drill string (rpm)
A	Action area of each swirling jet nozzle (m^2)
R	Radius of well bore (m)

1 Introduction

Lost circulation is one of the biggest challenges to drilling operators, which is both troublesome and costly. Operators have to deal with the additional problems caused by lost circulation during the construction and completion stages of the well, which directly affects the non-productive time and economic performances [1–3]. In recent years, the occurrences of lost circulation events have increased because drilling operators have to intensify their search into deeper reservoirs and start to drill in the depleted or partially depleted formations [4–6].

In the early times, the drilling process was often interrupted when encountering lost circulation, because the available technology was limited. With the rapid development of drilling technology, there were many remedial methods developed to tackle the lost circulation without interrupting the operations of drilling [7,8]. In order to control the lost circulation, many methods including pills, squeezes, cement plugs were employed, and lots of lost circulation materials (LCMs) and well-strengthening materials (WSMs) were added into the drilling fluid, such as rubber, cement, fiber, polymer, gel, micro-powdered cellulose. However, the plugging effectiveness was not always satisfactory, because the essence of these methods is completely dependent on the properties of the LCMs or WSMs [9,10]. For example, the LCMs or WSMs must have good adaptability to the loss formation. Also the type of material, concentration and size distribution of the LCMs or WSMs are all important factors to improve the plugging effectiveness. Moreover, the rheology and loss characteristics will certainly be affected when the drilling fluid is heavily laden with LCMs or WSMs, which are critical in deep wells or depleted formations. Then, the pressure-bearing capacity of the plugged zone was often not sufficient, which may result in a circumstance that lost circulation could happen again in the drilling operation after the pretreatment due to the complex down-hole situations and different sizes and shapes of leakage passages. In general, the conventional lost circulation management techniques seem to have reached their limit in plugging effectiveness and become ineffective in deep or depleted leakage formations.

Nowadays, a prevalent notion on lost circulation management is that the preventive treatment is more effective than remedial treatment, especially for depleted and natural fractured formations [11,12]. And many significant achievements have been obtained by preventive treatments [13,14]. Related literatures reveal that these successes are not only because of the advanced techniques, but also because of the progression of the theories of pretreatments, such as stress cage theory [15,16], fracture closure stress theory [17] and fracture propagation resistance theory [18]. Based on these theories, common preventive treatments including constantly strengthening the wellbore [19], improving the wellbore pressure containment[20], propping the fracture[21], keeping the fracture stable, building integrity around the region of the wellbore, and widening the narrow mud weight window [22] are developed instead of simply through “plugging the facture and throat”.

As asserted in a number of previous studies, in order to obtain the effectiveness of preventive treatments in deeper or depleted reservoirs, it is of great significance to improve the pressure-bearing capacity of wellbore. That is, the LCMs or MSMs in drilling fluid acted as sealing materials should enter into the fracture in a quick, efficient, and timely manner and form a more durable plugging in the fracture. Based on this idea, a special equipment for lost circulation control while drilling is designed, which employs the hydraulic energy to push the granules in drilling fluid into the fracture and “an artificial borehole wall” is formed to improve the wellbore pressure containment.

In this paper, the structure and working principle of the hydraulic tool are illustrated and a new plugging and sealing technology while drilling is developed. The hydraulic energy of swirling jet rather than the chemical characteristics of LCMs is mainly applied in this technology to control the leakage, and thus it has no special requirements for drilling fluid system and drilling operation. Favorable performances of this new tool have been manifested in laboratory tests and later oilfield applications.

2 Structure and Working Mechanism of the Hydraulic Tool

2.1 Structure Design

The structural design of the tool comprises an upper and a lower box joint, a main body, a hydraulic energy distribution device, relief-holes, seal assemblies, check rings, and swirling jet nozzles, as shown in Fig. 1.

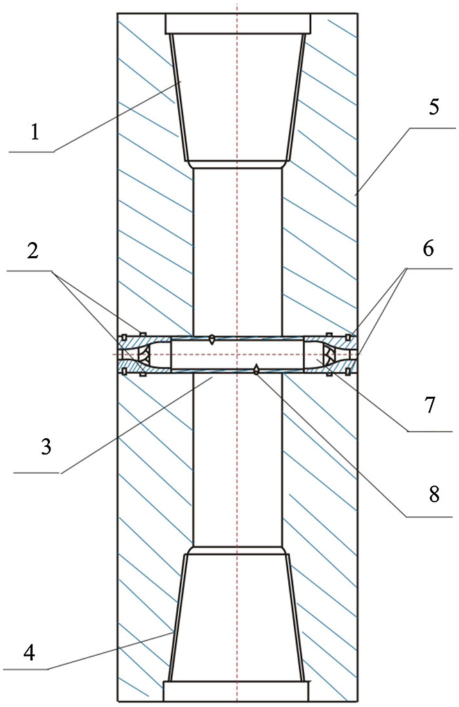

Fig. 1 Structure design of the tool. 1 upper box joint, 2 check ring, 3 hydraulic energy distribution device, 4 lower box joint, 5 main body, 6 seal assembly, 7 swirling jet nozzle, 8 relief-hole

The tool is designed to run as a component of the bottom hole assembly (BHA) while drilling in the deeper or depleted formations where lost circulation may occur. For example, it can be installed between the drill collar and drill bit. Thereinto, the upper and lower box joints are used to provide the threaded connection with the main body and drill string. The hydraulic energy distribution device is the key component of the tool, which is applied to allocate reasonable flow rate of drilling fluid to swirling jet nozzles and drill bit nozzles. The allocated drilling fluid will provide an impact effect in a form of swirling jet when the fluid flows through swirling jet nozzles. Two relief-holes on the hydraulic energy distribution device are installed in the form of one up and one down and interlaced horizontally to balance pressure.

2.2 Working Mechanism

In the process of drilling, swirling jet generated by the swirling jet nozzles is in a diffusive state and possesses three-dimensional velocity, which ensures its capacity of diffusion and entrainment. Meanwhile, the hydraulic power of swirling jet offers an additional lateral pressure acting on the borehole wall. So, the LCMs or WSMs in drilling fluid are forced to move and enter into the porous or naturally fractured zone "willingly" rather than accumulate on the wellbore wall under the entrainment and impact effect of swirling jet.

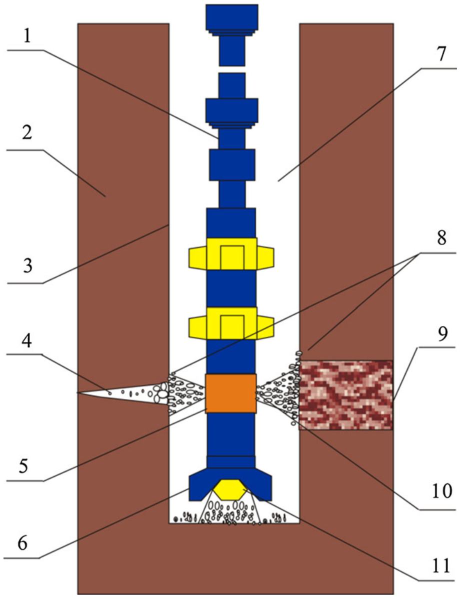

Fig. 2 Schematic of working mechanism. 1 BHA, 2 formation, 3 borehole wall, 4 natural fracture, 5 hydraulic tool, 6 drill bit, 7 annulus, 8 plugged zone, 9 leakage zone, 10 swirling jet nozzle, 11 bit nozzle

After the optimized granules (i.e., the median granule size should be equal to one-third of the fracture width) enter into the thief zone, LCMs bridging at the throat of fracture makes granules fill the rest space and leakage passage gradually disappears to form a plugged zone, which acts as a wedge to hold the fracture open and result in an increase in the hoop stress. Under the pressure difference between the swirling jet and formation pressure, the plugged zone is compressed further, which will enhance the strength of the sealing layer. The immobile mass accumulated in the leakage passage will become more stable and have a better crush strength, so the objective of lost circulation control while drilling is achieved. The schematic of working mechanism is presented in Fig. 2.

According to the preceding analysis, the tool generates two types of effect at the leakage zone: impact effect of swirling jet and plugging effect of lost circulation materials. The combination of these effects enables to induce a thin "artificial wall" with high strength at the leakage formation so as to enhance the pressure-bearing capacity of formation and avoid the potential occurrence of lost circulation.

3 Optimization of Working Parameters

According to working mechanism of hydraulic tool, the allocation of hydraulic power is the key to the safety of drilling and the success of lost circulation control while drilling. As a matter of fact, the essence of the hydraulic distribution is the distribution of the flow rate of drilling fluid to the drill bit nozzles and the swirling jet nozzles of the tool. Supposing that

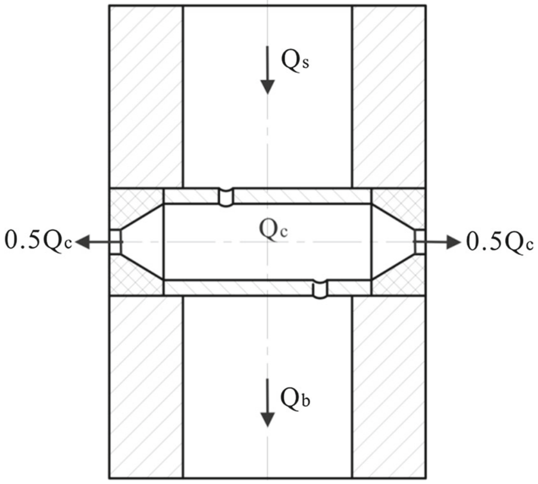

Fig. 3 Diagram of flow rate allocation

there is inadequate drilling fluid allocated to swirling jet nozzles, "artificial wall" formed on the borehole is unable to plug and seal, while if there is excessive drilling fluid, borehole problems (bit balling or wellbore collapse because of excessive erosion) may occur. Meanwhile, drilling parameters are also crucial to the effectiveness of plugging in operation.

3.1 Allocation of Flow Rate

Drilling fluid pumped into borehole is distributed scientifically into two parts during in drilling operation: one part of the drilling fluid flows into bottom hole through nozzles of bit, the other into annulus through swirling jet nozzles of the tool, shown in Fig. 3. To ensure the effectiveness of plugging and sealing while drilling, the distribution of flow rate is supposed to meet the following principles: hydraulic energy allocated to bit nozzles is to guarantee the cleanliness of bottom hole and carry cuttings, while the other distributed to the nozzles of hydraulic tool is to ensure the form of tough shield on the leakage formation with little erosion to the borehole wall.

According to the calculation principle of parallel pipeline (the flow rate of upstream pipeline is equal to the sum of flow rate of each branch pipeline) [23], the flow rate of rig pump can be expressed as:

$$Q_s = Q_b + Q_c \tag{1}$$

where Q_s is the flow rate of rig pump, which is obtained in drilling design; therefore, it is a constant in certain operating condition; Q_b and Q_c are the flow rate of drill bit nozzles and swirling jet nozzles, respectively.

Let I denote the flow rate ratio of Q_c to Q_s, that is: $I = Q_c/Q_s$, thus:

$$Q_b = (1 - I)Q_s \quad \text{or} \quad Q_c = IQ_s \tag{2}$$

If the flow rate ratio I is set during operating design, Q_b and Q_c can be calculated by Eq. (2). For calculation of circulating pressure loss is rather complex in drilling design, the calculation model of hydraulic parameters has been simplified within allowed calculation accuracy. The fundamental assumptions of drilling fluid are introduced as follows: (1) it is incompressible ideal fluid; (2) its rheological model is the Bingham-plastic fluid model; (3) its flow regime is isothermal turbulent flow, and then the diameters of bit nozzles and swirling jet nozzles and related hydraulic parameters can be obtained by following equations.

(1) Pressure drop of drill bit and hydraulic tool
Based on the rule of thumb [24], after taking drill bit and hydraulic tool as a whole, its pressure drop is as follows:

$$p_b = p_s - K_L Q_s^{1.8} \tag{3}$$

where p_b is the pressure drop of drill bit and hydraulic tool, p_s is the rig pump pressure, and K_L is the circulating pressure loss coefficient, which is related to the well depth L.

(2) Equivalent diameter of drill bit nozzles and swirling jet nozzles

In accordance with the Bernoulli equation, p_b can be changed into:

$$p_b = (1 + \xi)\frac{\gamma v_e^2}{2g} \tag{4}$$

where ξ is the coefficient of local resistance, γ is the unit weight of drilling fluid, v_e is the equivalent jet velocity of drill bit nozzles and swirling jet nozzles, g is the acceleration of gravity.

Let $C = \sqrt{1/1 + \xi}$ denote the discharge coefficient of nozzle, which takes a value between 0 and 1 corresponding to resistance coefficient of nozzle. Then, Eq. (4) can be changed into:

$$p_b = \frac{\gamma v_e^2}{2gC^2} \tag{5}$$

Substituting $\gamma = \rho_w g$, $v_e = Q_s/A_o$, $A_o = \frac{\pi}{4}d_e^2$ into Eq. (5) yields:

$$d_e = \sqrt[4]{\frac{4\rho_w Q_s^2}{5\pi^2 C^2 p_b}} \tag{6}$$

where d_e is the equivalent diameter of drill bit nozzles and swirling jet nozzles, A_0 is the total equivalent area of nozzles, ρ_w is the density of drilling fluid.

According to $\frac{Q_{\mathrm{b}}}{Q_{\mathrm{s}}} = \frac{d_{ej}^2}{d_{\mathrm{e}}^2}$, thus:

$$d_{ej} = \sqrt{\frac{Q_{\mathrm{b}} d_{\mathrm{e}}^2}{Q_{\mathrm{s}}}} \tag{7}$$

where d_{ej} is the equivalent diameter of bit nozzles.

Similarly, the equivalent diameter of hydraulic energy distribution device can be expressed:

$$d_{\mathrm{f}} = \sqrt{\frac{Q_{\mathrm{c}} d_{\mathrm{e}}^2}{Q_{\mathrm{s}}}} \tag{8}$$

where d_{f} is the equivalent diameter of hydraulic energy distribution device.

The equivalent diameter of swirling jet nozzles is related to the flow velocity of swirling jet. In the design of hydraulic parameters, the flow velocity of swirling jet is defined first; then, the equivalent diameter of swirling jet nozzles is expressed:

$$d_{\mathrm{c}} = \sqrt{\frac{40 Q_{\mathrm{c}}}{\pi v_{\mathrm{c}}}} \tag{9}$$

where d_{c} is the equivalent diameter of swirling jet nozzles, v_{c} is the jet velocity of swirling jet nozzle.

(3) Pressure drop of hydraulic tool

Similarly, in accordance with the Bernoulli equation, the pressure drop of hydraulic tool can be expressed:

$$p_{\mathrm{c}} = \frac{4\rho_{\mathrm{w}} Q_{\mathrm{c}}^2}{5\pi^2 C^2} \left(\frac{1}{d_{\mathrm{f}}^4} + \frac{1}{d_{\mathrm{c}}^4} \right) - \frac{4\rho_{\mathrm{w}} Q_{\mathrm{c}}^2}{5\pi^2 d_{\mathrm{f}}^4} \tag{10}$$

where p_{c} is the pressure drop of hydraulic tool.

(4) Jet velocity of drill bit nozzles is expressed:

$$v_{\mathrm{j}} = \frac{40 Q_{\mathrm{b}}}{\pi d_{ej}^2} \tag{11}$$

where v_{j} is jet velocity of drill bit nozzles.

(5) Impact force of drill bit jet

Based on the momentum theorem, the impact force of drill bit jet is formulated as:

$$F_{\mathrm{j}} = \frac{\rho_{\mathrm{w}} Q_{\mathrm{b}}^2}{25\pi d_{ej}^2} \tag{12}$$

where F_{j} is the impact force of drill bit jet.

(6) Bit hydraulic horsepower is expressed:

$$N_{bj} = p_{bj} Q_{\mathrm{b}} \tag{13}$$

where N_{bj} is the hydraulic horsepower of drill bit.

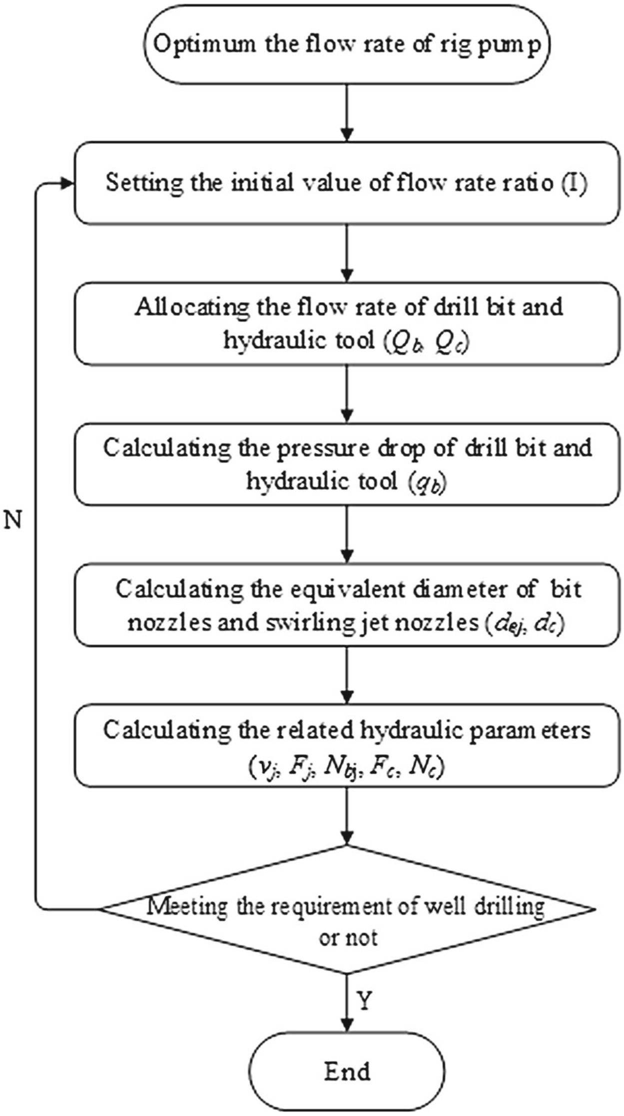

Fig. 4 Calculating process of flow rate distribution

(7) Impact force of swirling jet is expressed:

$$F_{\mathrm{c}} = \frac{\rho_{\mathrm{w}} Q_{\mathrm{c}}^2}{25\pi d_{\mathrm{c}}^2} \tag{14}$$

where F_{c} is the impact force of swirling jet.

(8) Swirling jet nozzle hydraulic horsepower is expressed:

$$N_{\mathrm{c}} = p_{\mathrm{c}} Q_{\mathrm{c}} \tag{15}$$

where N_{c} is the hydraulic horsepower of hydraulic tool.

If hydraulic parameters calculated by the first set value I unable to meet actual drilling operation, the ratio of Q_{c} to Q_{s} needs to be reset until calculated hydraulic parameters meet the need of the drilling operation. The calculating process of hydraulic-power allocation is shown in Fig. 4.

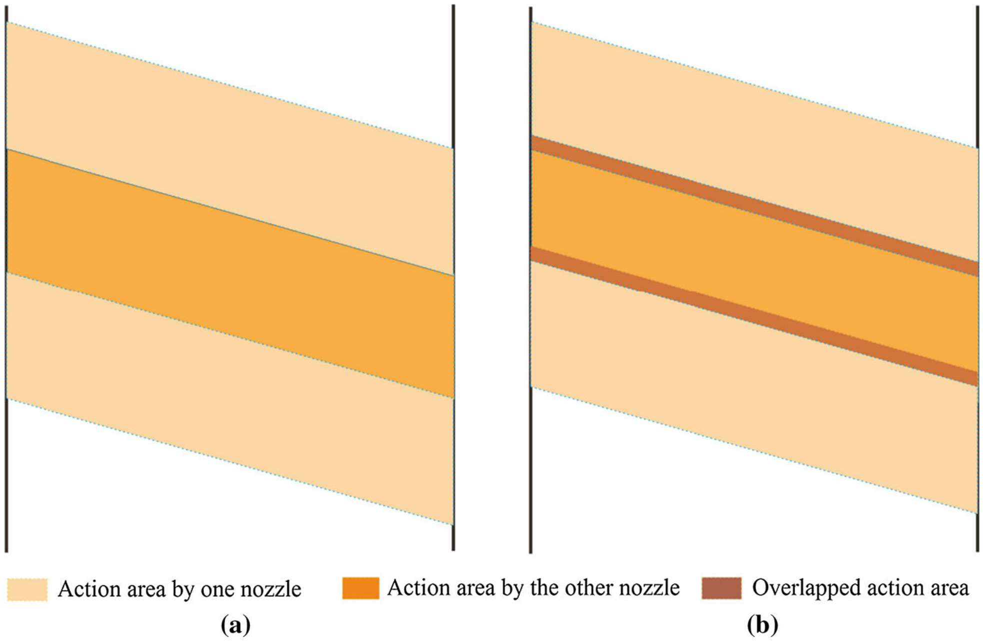

Fig. 5 Ideal operating modes of the hydraulic tool. **a** Action area precisely covers the blank area. **b** Action area overlaps partially

Table 1 Mechanical properties of rock samples

Sample	Lithology	Hardness (MPa)	Compressive strength (MPa)	Rock drillability
1	Siltstone	526	26.5	3.82
2	Packsand	483	21.3	3.68
3	Mudstone	571	29.5	4.95
4	Glutenite	893	54.2	6.70
5	Limestone	1274	127	8.65

3.2 Optimization of Drilling Parameters

According to the structure design of lateral symmetrical double nozzles, the ideal operating mode of the hydraulic tool in rotary drilling is as follows: action area of swirling jet on borehole wall by one nozzle precisely covers the blank action area omitted by other jet (shown in Fig. 5a), or there is minor overlapped action area by two swirling jets as shown in Fig. 5b, which ensure action area of swirling jet by both nozzles can cover the borehole wall thoroughly.

Therefore, it is necessary to design the rate of penetration (ROP) to guarantee that drilling footage is less than height of action area on the borehole within the time that the tool rotates in semi-cycle. That is:

$$n \geq \frac{\pi R v_{pc}}{60A} \tag{16}$$

where v_{pc} is the ROP, n is the rotation speed of drill string, A is the action area of each swirling jet nozzle while drill string rotates a round, R is the radius of well bore.

When the ROP is constant, rotation speed of drill string needs to achieve the following requirements: (1) satisfy Eq. (16) to guarantee the integrity of "artificial borehole wall", (2) unable to be rather fast; otherwise, the time of swirling jet acting on borehole wall is too short, which will sabotage the plugging performance of hydraulic tool.

4 Laboratory Experiments

4.1 Erosion Experiment of Swirling Jet

The tool is installed near the drill bit, where thick mud cake on the corresponding position of borehole wall has not been formed. Therefore, swirling jet will impact the borehole wall directly, so it is necessary to discuss whether there is an erosion effect of swirling jet to the borehole wall or not.

Five rock samples from lost circulation formation in Tarim oilfield are collected to conduct an experiment on rock threshold pressure under swirling jet erosion. Mechanical properties of these samples are presented in Table 1. Experiment parameters: drop pressure of nozzle is 10 MPa, acting

Table 2 Threshold pressure of rock samples

Sample		1	2	3	4	5
Threshold pressure (MPa)	Confining pressure 0.5 MPa	8.3	7.4	9.0	12.2	17.8
	Confining pressure 1.0 MPa	10.2	9.6	11.5	14.3	20.0
	Confining pressure 1.5 MPa	13.4	12.5	14.9	17.8	24.2

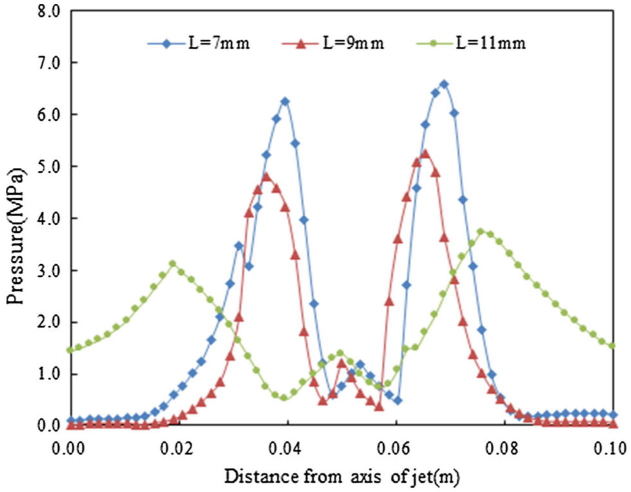

Fig. 6 Pressure distribution curves of swirling jet

time of swirling jet is 12 s, spray distance of the swirling jet is 4 times of the diameter of nozzle; confining pressures are 0.5, 1 and 1.5 MPa, respectively. Results of the experiment are given in Table 2.

Results of the experiment indicate: (1) rock threshold pressure under jet erosion grows with the increase in its hardness, compressive strength, drillability and confining pressure; (2) rock samples will be damaged when the sheer stress created by swirling jet is greater than its internal bond strength.

At the same time, a numerical simulation on pressure distribution of swirling jet is conducted based on the above-mentioned experiment parameters. And the spray distance, which is the distance from the outlet of swirling jet nozzle to borehole wall, is set to 7, 9, and 11 mm, respectively.

The simulation results (shown in Fig. 6) manifest that the peek pressure of swirling jet is declined with spray distance growing, and it is less than the obtained rock threshold pressure. Evidently, the swirling jet acting on the borehole wall is not enough to cause erosion damage to the borehole wall.

4.2 Experiment on Plugging and Sealing While Drilling

(1) Experimental apparatus and materials

Experimental apparatus based on working mechanism of the hydraulic tool to simulate the process of plugging and sealing is shown in Fig. 7.

In this apparatus, rotary vertical shaft, simulated as the drilling string, is a hollow pipe, whose rotate speed and descent velocity are able to adjust under the combined control of electric driver and manual control apparatus. And a high-pressure nitrogen gas bottle is employed as a rig pump to introduce drilling fluid laden with designed LCMs into the mimic borehole. Also, a hydraulic choke is installed on the returning pipe, which is used to control confining pressure.

The materials used in experiment are as shown below:

The drilling fluid employed in this experiment is polysulfonate system, which is widely used in deep wells. Drilling fluid composition is as follows: 3% clay fluid + 5% NaCO$_3$ + 0.3% FA-367 + 0.2% XY-27 + 5% SPNH + 3% SMP-1 + 2% SMC + 2% FT-1. The density of polysulfonate system is 1.2 g/cm^3.

In order to exclude the effect of chemical property on loss control, commonly used inert materials on the site including rigid particle, nut shell and rubber granule are employed as the LCMs. So, the drilling fluid system for lost circulation while drilling is: polysulfonate drilling fluid + 1.0%A rigid particles + 0.5%B, C, D, E, F rigid particles + 0.5%B, C, D nut shell + 0.5%B, C, D, E rubber granule. Table 3 shows the relationship between granule grade and particle size of LCMs.

Cylindrical artificial cores (shown in Fig. 8) with vertical and horizontal factures are utilized to simulate fractured formation. The height, inner and outer diameter of the artificial core is 40, 7.3 and 10 cm, respectively. The width of the fracture is 2 mm.

Owing to the fact that the diameter of artificial cores in experiment is rather slim, to simulate the actual application effect of the tool, a small-sized hydraulic tool, whose external diameter is downsized, is employed in the laboratory experiment to guarantee the result that the distance from the outlet of swirling jet nozzle to the inner wall of artificial core in experiments is equal to that of field operation. The diameter of swirling jet nozzle is 2.5 mm. Other experimental parameters such as rotate speed of rotary vertical shaft, property of drilling fluid and hydraulic parameters are obtained by computing model of hydraulic-power allocation in part 3.

(2) Experiment design

Experiments are conducted into two groups, the plugging effectiveness with the tool and without it are simulated, respectively. Experimental procedures with the tailor tool are shown in Fig. 9.

Experimental procedures without the tailor-made hydraulic tool are similar to the experiment with one. However, tailor-

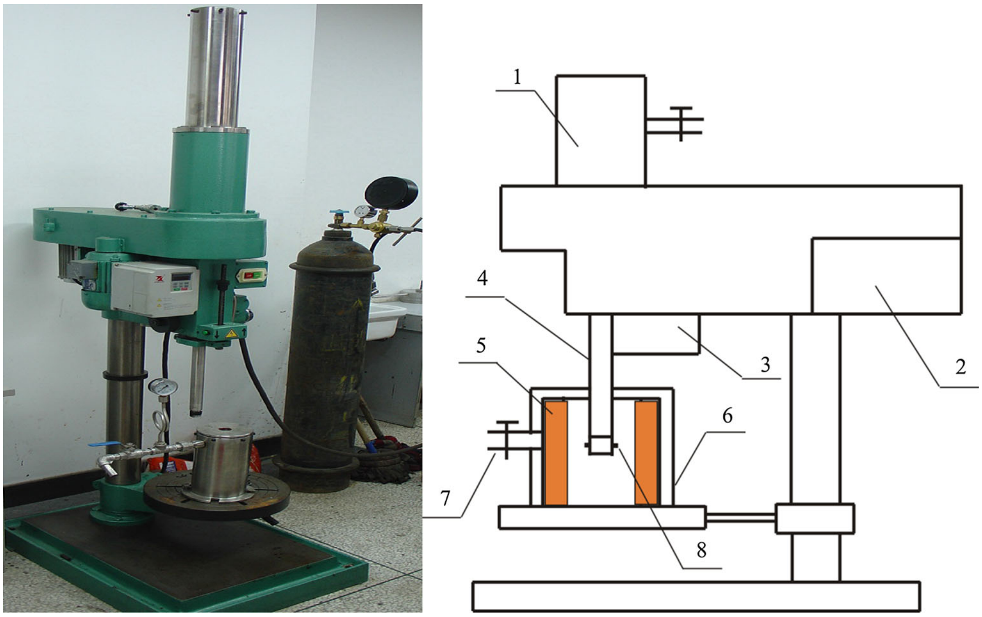

Fig. 7 Schematic diagram of experimental apparatus. 1 drilling fluid container, 2 electric driver, 3 manual control apparatus, 4 rotary vertical shaft, 5 artificial core, 6 mimic borehole, 7 returning pipe, 8 tailor-made hydraulic tool

Table 3 Relationship between granule grade and particle size

Granule grade	A	B	C	D	E	F
Mesh number	10–20	20–40	40–60	60–80	80–100	100–120
Size (mm)	2.0–0.9	0.9–0.45	0.45–0.3	0.3–0.2	0.2–0.15	0.15–0.125

Fig. 8 Cylindrical artificial cores with facture

made hydraulic tool installment is eliminated in preparation stage and pressuring stage is added before the end of the experiment.

(3) Experiment results

Experiments are conducted under experimental conditions shown in Table 4, and comparison experiment results are shown in Fig. 10.

The results indicate that the performance of plugging is undesirable without the application of the tool as granules are not closely stacked and 2 mm facture is not plugged effectively. While with the employment of the tailor-made hydraulic tool, the plugging effectiveness is favorable as granules are tightly stacked in the fracture and fracture is plugged tightly. Evidently, a favorable plugging performance (shown in Fig. 11) is obtained by using this tool, which is clearly illustrated under the zoom-stereo microscope (ZIESS stemi SV-11).

4.3 Evaluation on Pressure-Bearing Capacity of Plugged Zone

Hydrofracturing test is employed to evaluate the pressure-bearing capacity of plugged zone. Pressure-bearing apparatus is presented in Fig. 12.

These two kinds of artificial cores gained in above experiments are fractured, respectively, by employing the pressure-bearing apparatus. Base mud is employed as fracture fluid, and their collapse curves of plugged artificial cores are shown in Fig. 13.

Collapse curves demonstrate that the pressure-bearing capacity of artificial core with application of the tool reaches to 8.3 MPa while pressure-bearing capacity of without one is 4.9 MPa in this experiment. Therefore, the evaluation experiments manifest a favorable performance of this tool on plugging and sealing while drilling.

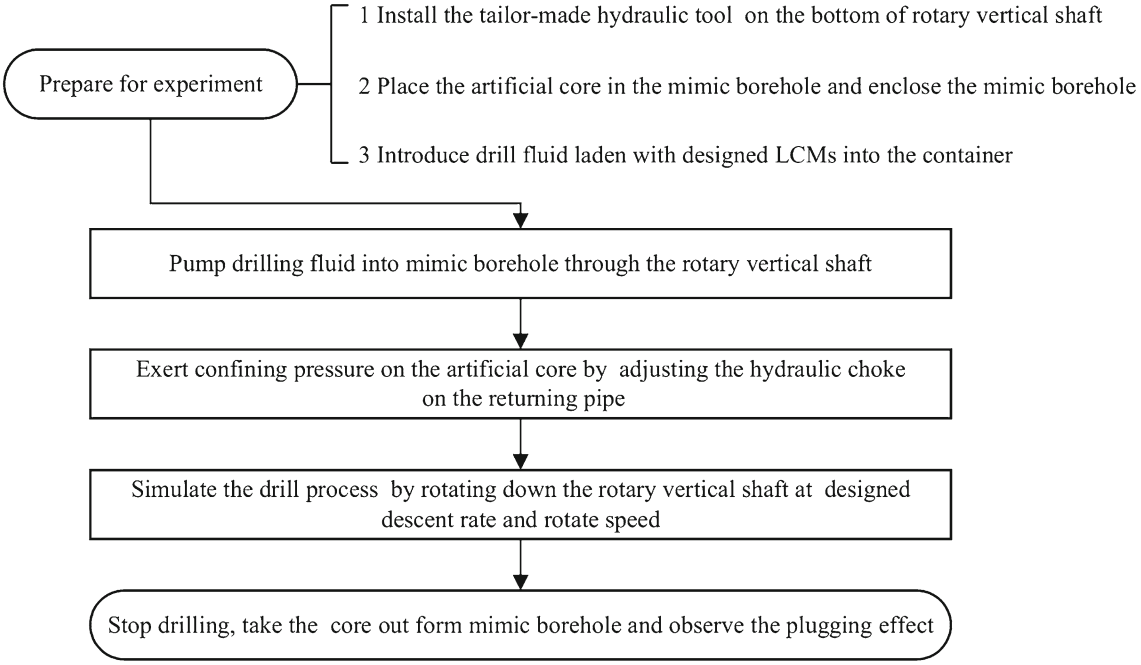

Fig. 9 Experimental procedures with the tailor tool

Table 4 Experimental conditions of plugging and sealing while drilling

Experimental group	Confining pressure MPa	Rotate speed r/min	Descend rate m/min	Duration of hold pressure min
With the tool	5	80	0.1	/
Without the tool	5	80	0.1	15


(a) **(b)**

Fig. 10 Comparison of experiment results. **a** Without the tool. **b** With the tool

In laboratory experiment, the sizes of artificial core and operating pressure are restricted by experimental circumstance. Compared with the laboratory experiment circumstance, the thickness of plugged zone formed in actual oilfield working condition is greater than that of artificial cores, so the capacity of plugged zone formed by the tool in oilfields is higher than 8.3 MPa.

5 Field Applications

Field tests of the hydraulic tool have been carried out in various oilfields, such as Tarim oilfield, Zhongyuan oilfield, Shengli oilfield. The formations where the test conducted includes deep fractured formations, depleted formations. In

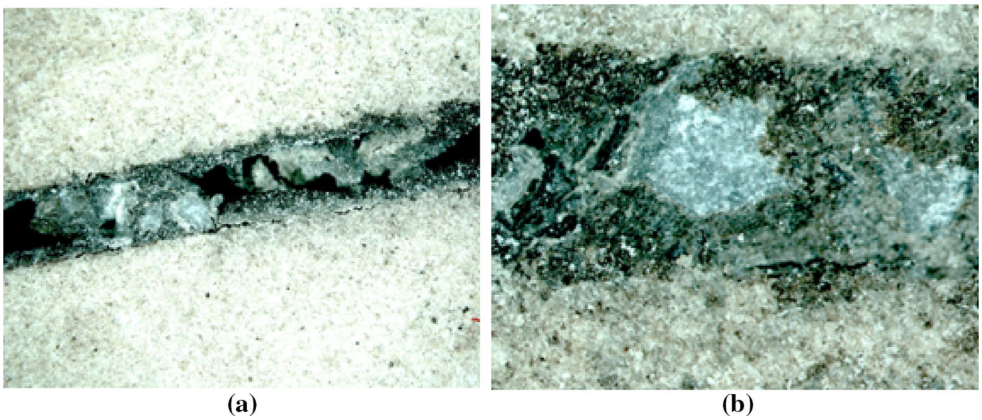

Fig. 11 Experiment results under zoom-stereo microscope. **a** Without the tool. **b** With the tool

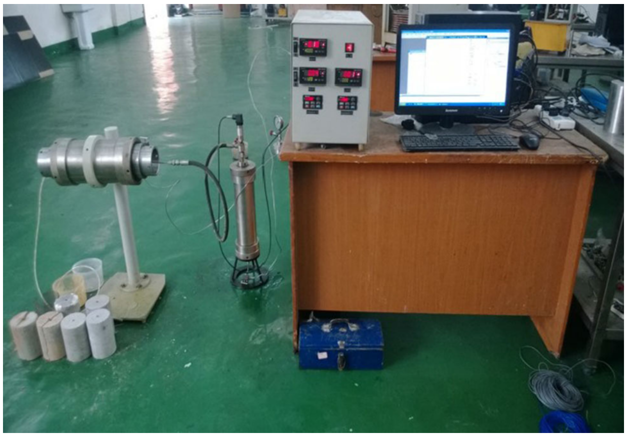

Fig. 12 Experiment apparatus of pressure-bearing capacity

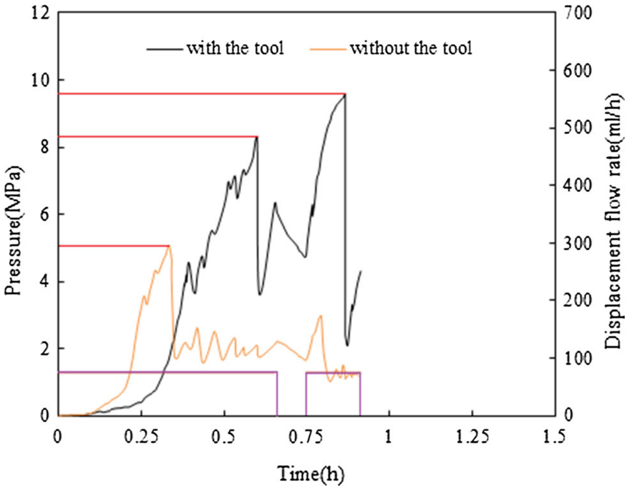

Fig. 13 Collapse curves of plugged artificial cores

order to verify the plugged performance of the tool, the operation conditions with the tool are almost the same compared with those without the tool in the vicinity.

5.1 Application in Well D2-4 of Tarim Oilfield

Based on drilling data in adjacent wells, lost circulation emerges frequently in Palaeogene system, which is mainly caused by natural and induced fractures. Hence, the tool is tested in Palaeogene system of the forth drilling section (its diameter is 215.9 mm) of D2-4, and the test depth ranges from 5686 to 6071 m.

The drill parameters of lost circulation management are as follows: flow rate 28 L/s, pump pressure 22–24 MPa, rotate speed 70 rpm, drilling fluids polysulfonate system, drilling fluid density 2.35–2.36 g/cm^3, and total concentration of LCMs 3–6%. The length of hydraulic tool is 460 mm, its outer diameter is 190mm, and inner diameter is 75 mm. According to the calculation mode of hydraulic parameters, allocated flow rate of the hydraulic tool is reached to 16% of the total flow rate of rig pump and the diameter of swirling jet nozzle is 6.39 mm. The results are presented in Table 5.

The test result indicates that the probability of lost circulation is decreased sharply. Compared with D2-2 and D2-5, the number of lost circulation in D2-4 is reduced by 87.5 and 84.6%, respectively, and the leakage volume of D2-4 is reduced by 92.4 and 89.9%, respectively. What is more, the situation of drilling interruption caused by lost circulation does not happen in the leakage zone of D2-4.

5.2 Application in Well PC-51of Zhongyuan Oilfield

Well PC-51 is an exploitation well located at Pucheng structure with 2980 m designed well depth. According to the data of drilled well, Shahejie formation is the main leakage zone in this structure, and high permeability and depleted formation pressure are the primary reasons for lost circulation in this formation. Pressure coefficient of this reserve is around 0.4–0.65. The tool is installed on BHA when well depth reaches 2378 m. The operation parameters from 2397 to 2980 m are as follows:

Table 5 Comparison leakage volume between D2-5 and adjacent wells

Well number	Orientation	Well section (m)	Leakage volume (m^3)	Times of lost circulation	Times of stop drilling
D2-2	NE320m	5757–6081	827	16	14
D2-5	SW260m	5771–5950	624	13	10
D2-4	Test well	5685–6071	63	2	0

BHA: 215.9 mm G55 PDC bit + 190 mm tool + 158.8 mm single bend PDM+ 158.8 mm drill collar + 127 mm heavy weight drilling pipe + 127 mm drill pipe + Kelly.

Drilling parameters: drilling mode is compound, ROP is 7.48 m/h, pump pressure is 15 MPa ∼ 17 MPa, flow rate of rig pump is 30L/s, designed jet velocity of swirling jet nozzle is 20 m/s, and minimum annular velocity is 1.01 m/s.

Property of drilling fluid: light polymer system, density is 1.18–1.20 g/cm^3, viscosity 60–113 s, solid concentration 9%.

Walnut shell (8%), saw dust (1%) and natural asphalt powder (3%) are added to the drilling fluid as LCMs after the depth of 2300m.

During the drill process, the pressure is built up to 11.6 MPa and lost circulation does not exist in the follow-up drilling and cementing operation. Repeat formation test (RFT) has been conducted after drilling work, and the result manifests that the minimum pressure coefficient of this section is just 0.37, while well PC-48 which is 322 m apart from PC-51 has been abandoned because of the vicious lost circulation at 2400 m.

6 Conclusion

A new hydraulic tool for lost circulation control while drilling is designed based on the notion of preventive treatment. The tool enables to prevent lost circulation effectively by employing the hydraulic power of jet generated by its lateral swirling jet nozzles.

On the basis of theoretical analysis on working mechanism, a new plugging and sealing technology while drilling is formed, its working parameters are optimized and a computing model for flow rate allocation is developed.

The laboratory experiments are designed to evaluate and validate the plugging effectiveness of the tool. Experiment and simulation results show that the hydraulic pressure of swirling jet has not caused erosion damage to the surrounding rock, and the maximal value of pressure-bearing capacity of experimental core is increased to 8.3 MPa after employing this tool.

Field applications in deep wells and depleted reservoirs manifest that the plugging effectiveness is improved greatly by applying the hydraulic tool, and the bearing capacity of formation in depleted reservoir is up to 11.6 MPa.

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