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Paper

SOME ADVANCES IN ULTRAHIGH PRESSURE JET ASSISTING ROCK-BREAKING TECHNIQUE: THEORY AND EXPERIMENT

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ABSTRACT

Down-hole boost compressor is the core technique of ultrahigh pressure jet drilling, which can increase rate of penetration in the deep well. In recent years, some advances have been made in theories and experiments. In theoretical side, boosting principle was proposed and the design theory was set up, thus the hydraulic structure and performance were got. Adopt with mechanism of jet flow Attachment and Switch in fluidic element, it was used for the directional control unit which could control the commutation motion of piston. Based on the theoretical research and the concept of threshold pressure, China University of Petroleum successfully manufactured models, and several experiments were done. The experiments of nozzles' materials and prototype were done in the laboratories, and test result verified that polycrystalline diamond was optimized as the material of nozzle, and the working life is 80 hours. Five field experiments were done in the Zhongyuan Oil Field and Tuha Oil Field in succession, and test result verified that the working lives of booster's key components have exceeded 40 hours. The above researched have enriched and developed the theory of ultrahigh pressure jet assisting rock-breaking, and promoted field experiment and application.

1. INTRODUCTION

The ultrahigh-pressure-jet-flow as one of the key methods to increase rate of penetration, has been widely studied recently^[1]. And down-hole pressure intensifier which comprised of a hydraulic motor and booster pump is the core equipment for jet drilling^[2]. The hydraulic motor-booster pump combination is the basis for turbo-booster, screw-booster, and piston-booster which can be made as fluidic and valve^[3,4]. Due to its structural simplicity, the piston-booster can be designed in a short form thus to be used in deviated and horizontal wells^[5,6]. After many years' research and development, China University of Petroleum has successfully manufactured a model in 2005 (see in **Figure 1**).

In this paper, the following issues in research of the down-hole boost compressor were studied: boosting theory, the design theory of downhole boosting compressor, the mechanism of reverse control, and threshold pressure. Two lab experiments and five field experiments were discussed. These studies and results play a guiding role to the design and improvement of fluidic down-hole pressure intensifier.

2. ADVANCES IN THEORETICAL RESEARCH

In the work process of down-hole boost compressor, the piston and fluidic element play the most important role, thus it is very necessary to research the design theory of fluidic structure and the fluidic characteristic about the piston and fluidic element. Piston boosting technique mainly involves design of the cylinder, and switch structure for piston movement which is the key to ensure the pressure intensifier to be functional properly. When the piston is moving along the cylinder, the jet flow inside the fluidic element flows downward steadily along one side of the wall. When the piston moves to the dead center, flow becomes stagnant, then it switches quickly under the back pressure and control flow. And apply the fluid mechanics net design method to analyses two sub-processes (charge and restoration strokes) of the piston for the first time.

2.1 Boosting Theory

Piston-booster is designed to increase the small-scale fluid pressure by converting the pressure energy to mechanical energy using a hydraulic motor and then back transform the mechanical energy into pressure energy using a booster pump^[7]. The principle for piston-booster is analyzed below according to hydrostatics. (**Figure 2:** Boosting theory of piston-booster).

In the charge stroke, the two upper chambers of piston cylinders are connected to upstream high-pressure fluid, and the pressure energy is passed on to the upstream chambers. In contrast, the two downstream chambers of piston cylinders are connected to downstream low-pressure fluid thus have a relatively low pressure. In consequence, the pressure difference is formed between upstream and downstream part of the cylinder, which drives the

piston to move downward and convert the pressure energy into mechanical one. In this process, the output power P_{FM} is calculated in the follow equation ^[8]:

$$P_{FM} = (p_{uu}A_{uu} - p_{lu}A_{lu} + p_{ul}A_{ul} - p_{ll}A_{ll})V_{pistion}$$
(1)

When the piston moves downward, it compresses the fluid inside the plunger cylinder, and converts the mechanical energy back into pressure energy. The output power P_{BP} is:

$$P_{BP} = p_{bp} A_{bp} V_{pistion} \tag{2}$$

Ideally, i.e., when there is no leakage in the piston cylinder and plunger, we have:

$$P_{Fm} = P_{BP} \tag{3}$$

Plug equation (1) and (2) into (3), we get:

$$\frac{p_{bp}}{A_{bp}} = \left(p_{uu}A_{uu} - p_{ul}A_{ul} + p_{ul}A_{ul} - p_{ll}A_{ll}\right)$$
(4)

Equation (4) is boosting equation, and according to this equation we can get the guiding principle: the effect of boost pressure will be much better, if we increase the pressure difference between two pistons, or increase area of the gap between two pistons. This provides a clear guidance for booster design to improve the delivery pressure.

2.2 Design Theory of Booster

The flowpaths of fluidic down-hole pressure intensifier are made up of many components which form parallel and series connections in several ways. How to determine the delivery pressure and flow rate for each flowpath and its components is an very important problem in fluid mechanics. It has been solved by referring the hydraulic model.

2.2.1 Hydraulic Model

The work process of fluidic down-hole pressure intensifier consists of charge and restoration stroke^[9]. These two strokes need to be considered separately because they are different in flowpath structure and governed by different flowing laws.

For example, as shown in **Figure 3**, during charge stroke, the flow network for fluidic down-hole pressure intensifier in the charge stroke has four nodes and three branches. Apply mass conservation equation for each node and momentum conservation equation for each branch, we get:

$$Q = Q_1 + Q_2 + Q_3 \tag{6}$$

$$Q_1 = A_u Q_2 / A_l \tag{7}$$

$$\Delta p_{B1} = \Delta p_{B2} = \Delta p_{B3} \tag{8}$$

2.2.2 Hydraulic performance

Based on the hydraulic model described above and the structure of the prototype, we solved the flow network by using numerical simulation method and obtained the flow rate and pressure loss for each component of the pressure intensifier in charge stroke. The calculation results are listed in **Table 1**. The total pressure loss in terms of the data shown in table 1 is 9.3 MPa, which is very significant that a more optimized design is needed to decrease the total pressure loss.

2.3 Principle of Reversing Control

The fluidic element is the core component of directional control units of booster. The characteristic of attachment and switch of fluidic element plays a crucial role in the commutation characteristic of booster. And this characteristic can be simulated by using numerical simulation method^[10,11].

2.3.1 Fluidic Attachment

As shown in **Figure 4**, The fluidic element need to contact with load, lower side connect with piston cylinder which has two cylinders: upper piston cylinder and lower piston cylinder. Upper piston cylinder connects with output channels, and lower piston cylinder connects with exhaust channels. Because of pressure difference, piston will move along the cylinder.

Because the load between two sides of output channels is not symmetric in working condition, the jet flow will be deviated to one side and move downward, which is called "fluidic attachment". As shown in **Figure 5**, there are two separated vortexes, and these vortexes play a very improtant role. The structure of vortex on the one side of attachment is smaller and the pressure difference is much higher. So the smaller vortex generate a force to make the jet deflexion and attachment. The separated vortex on the upward side of splitter also plays an improtant role, force the streamlines flow downward steadily. Because the fluidic element has the characteristic of quasi-two-dimensional, the **Figure 6** can basically represent the characteristic of three-dimensional flow. As shown in the Figure 6, the pressure of the vortex's core on the left side of nozzle is -4.75MPa (The pressure of inlet is relative pressure, and setting value is zero). And the pressure on the right corresponding position is

-3.25MPa. This shows the structure of two sides of vortex is not symmetrical, intensity difference is obvious, and this difference contributes the forces of two sides of jet is not symmetrical too.

From the Figure 6, we also can find there is another separated vortex in the left exhaust channel, and the pressure of vortex's core is also lower. Meantime dynamic pressure changes into static pressure in the exhaust channel, the pressure rise to -1.6Mpa. There is 2.2 Mpa pressure difference between the two exhaust channels. The booster exactly makes use of the pressure difference, drives the piston move downward.

2.3.2 Fluidic Switch

Fluidic switch is the process in which the jet flow switches from one side of the attachment wall to the other side under the back pressure and control flow. This process which form a steady flow is simulated numerically in this paper.

Fluidic switch has two sub-processes: commutation and attachment (**Figure 7**), and it only takes 0.019s. When the piston moves to the dead center, flow becomes stagnant, as it were, the power of switch is from the high back pressure which produced by the flow stagnant. In other words, the separated vortex is the resistance to make fluidic switch, not the power. The fluidic attachment and fluidic switch are not just the same way, need to destroy the steadily structure, switch to the other side. The research about separated vortex plays an important role in the design of the fluidic element structure.

3. ADVANCES IN EXPERIMENTAL RESEARCH

Based on the theoretical research and the concept of threshold pressure, China University of Petroleum successfully manufactured models, and several experiments were done.

3.1 Governing Principle of Delivery Pressure

The booster is designed to break rock directly^[12]. But how to define the span of the delivery pressure of booster need to be researched. Below research is based on the damage mode of rock and mechanism of rock-breaking.

The mechanism of high pressure water jet rock-breaking is based on water erosion (**Figure 8**), and the mechanism of ultra-high pressure water jet rock-breaking is based on water hummer^[13,14]. The center area of rock tends to twist under ultra-high pressure jet, thus forms a concentration region of stress, in this region exist tensile stress around the center area, and these tensile stress act radial, and point to the center of jet, thus contribute to lots of surface cracks, and expand to the inside of rock. These cracks perform circles and circles, so rock gets broken(as shown in the **Figure 9**). This process of rock-breaking by ultra-high pressure jet is defined water hammer. The critical value form water erosion is defined as the first

threshold pressure, and the critical value form water hammer is defined as the second threshold pressure (as shown in the **Figure 10**, there are two obvious turn points, separately correspond with p_1 the first threshold pressure and p_2 the second threshold pressure). And

this process of rock-breaking by the ultra-high pressure jet is defined as "water hammer". The Down-hole boost compressor exactly makes use of this principle to design the structure of booster, control the delivery high pressure between the first threshold pressure and second threshold pressure.

3.2 Laboratory Experiment

3.2.1 Experiment of Nozzles' material

The characteristic of nozzle is the core technique of the ultra-high pressure PDC bit under the condition of 100-150Mpa pressure and jet speed of 800-1000m/s. The simulation of nozzle's erosion resistance in the laboratory is a new theme. Compared with the other lab experiments, we choose SEM (Scanning Electron Microscope), diameter measurement and weightless method to be the mainly appraisal procedures. Precision of diameter measurement can reach 0.01mm, and the precision of weightless method can reach 0.0001g. The PDC bit was simulated by the single nozzle.

The setup adopted WOMA high-pressure pump which produced in German (the pressure was 140 MPa, the capacity was 61 L/min, and the power was 154 Kw). The outside diameter of adoptive nozzle was 20mm, internal diameter was 1.25~1.395mm, the speed of jet was 600-700m/s. The materials included polycrystalline diamond and hard metal alloy.

As shown in **Figure 11** and **12**, the weight of nozzle which material was the hard metal alloy loosed as times go on, the change rate of weight and eroded rate increased too. After 80 hours, eroded rate can reach 48%, so we made the decision that the hard metal alloy couldn't meet the project challenge. As shown in **Figure 13** and **14**, the weight of nozzle which material is the polycrystalline diamond loosed as times go on, the change rate of weight and eroded rate increased too. After 80 hours, weight eroded can reach 32%, so we suggest that the polycrystalline diamond could meet the project requirement.

The above researches have enriched and developed the theory of ultrahigh pressure PDC, and promoted field experiment and application.

3.2.2 Experiment of Prototype

In the test well, reliability test about the down-hole boost compressor were done 10 times. Experiment facility included pressure gauges, nozzles, and testing conduit line etc. The booster connected with Kelly bar. After turned on the pump, we could hear the knock clearly, and observed the pulsate drilling fluid blew out of the nozzle (i.e. Figure 15). We also could verify the pulse characteristic from the data recording (i.e. Figure 16). The outlet pressure direct related to the capacity of inlet and the pressure difference of throttle. When the different SPP was set, we could also see that designed pressure loss dovetail with the actual

pressure loss. Simultaneously for the purpose of meeting the challenge of circulating pressure, the pressure ratio need to be increased.

3.3 The Field Experiment

China University of Petroleum has successfully manufactured two generation of down-hole boost compressor, and five field experiments were done in the Zhongyuan Oil Field and Tuha Oil Field in succession. For example, the latest field experiment was in 5-316, block of Wen-5, Tuha Oil Field(i.e. **Figure 17**). The down-hole boost compressor and ultra-high pressure PDC bit with dual-flow channel connected to the Kelly bar. When slurry bumping capacity was 34 l/s, and SPP was 14.0MPa, we could hear the knock clearly, and the frequency was about 2/s, all these all can prove that booster was in working order, the drilling data was shown in **Figure 18**.

The down-hole boost compressor and ultra-high pressure PDC bit with dual-flow channel worked 8.16h in this experiment. In the drilling process, the rate of penetration can reach 16.21 m/h, contrast to the other drilling technique with PDC bit in the same well, the rate of penetration increased 34.25%, contrast to drill only with PDC bit in the same well, the rate of penetration increased 60.1%, contrast to the other drilling technique with PDC bit in the same block, the rate of penetration increased 52.7%. These all can verify that the down-hole boost compressor achieved the goal about creasing the rate of penetration in the field.

4. CONCLUSIONS

In this paper, some hydraulic mechanical problems related to mechanism design and fluid mechanics were studied, and simulation results were presented. A series of experiment were done, and test data can be used to help design and optimize the fluidic downhole pressure intensifier.

- By applying hydrostatics, the principle of boosting was analyzed, and the boosting equation was set up. According to the equation, we can get the governing principle: the effect of boost pressure will be much better, if we increase the pressure difference between two pistons, or increase area of the gap between the two pistons.
- By applying mass conversation equation and momentum conversation, hydraulic models were set up. After solving the hydraulic models numerically, we obtained the flow rate and pressure loss for each component.
- By applying computation fluid dynamics, the turbulent flow of bistable jet fluidic element was simulated numerically, and the result shows the mechanics of attachment and switch, and we get the structure of microcosmic flow and characteristic of macroscopically flow. The time interval between the two sub-processes is very short, about 0.019s in our study; it was shown that choose fluidic element to be the reversing components was feasible and reliable.
- In the process of fluidic attachment, exists intense vortexes structure in the exhaust channels, and contribute to a pressure difference between the outlet channel and exhaust

channel. The pressure difference is one of the powers which drive the piston to move downward.

- According to the damage mode of rock and mechanism of rock-breaking, apply dynamic contact method. the ultra-high pressure jet assisted rock-breaking technique has been researched systematically. And the concept of first threshold pressure and second threshold pressure were proposed. Simultaneously shows the mechanics of rock-breaking under conditions of different jet pressures. The erosion damage occurs at the first threshold pressure, water hammer damage occurs at the second threshold pressure.
- Adopt with SEM, diameter measurement and weightless method to be the mainly appraisal procedures, the mechanics of nozzle erosion was researched. The results verify that apply the polycrystalline diamond to be the material of the nozzle was feasible and reliable, father improve working life of the downhole boost compressor.
- The prototype of downhole boost compressor was developed and manufactured. According to the results of laboratory experiments, the design feasibility and work reliability were verified. Simultaneously the results of experiments showed that the design objective of whole system reaches the requirement, and could meet the field use requirement.
- The results of field experiments showed that the rate of penetration could reach 16.21m/h which were using downhole boost compressor comply with ultra-high pressure PDC bit with dual-flow channel, contrasted to the rate of penetration which only used PDC in the same well, the rate of penetration increased 60.1%,. In the same block, contrast to the other combination drilling techniques comply with PDC, the rate of penetration could rise 52.57%, achieved the anticipated goal.

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NOMENCLATURE

- P_{FM} is the output power of fluid motor, watt;
- p_{uu} is pressure in upper chamber of upper piston cylinder, Pascal;
- p_{lu} is pressure in lower chamber of upper piston cylinder, Pascal;
- p_{ul} is pressure in upper chamber of lower piston cylinder, Pascal;
- p_{ll} is pressure in lower chamber of lower piston cylinder, Pascal;
- A_{uu} is the contact area of the piston pushed by p_{uu}, m^2 ;
- A_{lu} is the contact area of the piston pushed by p_{lu}, m^2 ;
- A_{ul} is the contact area of the piston pushed by p_{lu}, m^2 ;
- A_{ll} is the contact area of the piston pushed by p_{ll} , m^2 ;

 V_{piston} is the speed of piston, m/s

- P_{BP} is the output power of the boost bump, watt;
- p_{bp} is the pressure in boost bump, Pascal;
- A_{bp} is the area in cross section of plunger cylinder, m^2
- A_{μ} is the area in cross section of upper piston cylinder, m^2 ;
- A_l is the area in cross section of lower piston cylinder, m^2 .
- Q_1 is the flow rate of branch 1, m^3/s ;

- Q_2 is the flow rate of branch 2, m^3/s ;
- Q_3 is the flow rate of branch 3, m^3/s ;

 Δp_{B1} is the pressure loss of branch 1, Pascal;

 Δp_{B2} is the pressure loss of branch 2, Pascal;

 Δp_{B3} is the pressure loss of branch 3, Pascal.

TABLE

Name of Components	Flow Rate (<i>l/s</i>)	Pressure Lose _(MPa)
Output 1 in Fluidic Element	8.6	1.59
Exhaust 1 in Fluidic Element	19.4	7.01
Upper Piston Cylinder	8.6	7.38
Lower Piston Cylinder	4.3	1.81
Annular Flow Channel 1	19.4	0.11
Annular Flow Channel 4	15.1	0.003
Channel Connected with Low Pressure	12.9	0.31
Channel of the Centibar	8.6	0.02
Throttle Valve	15.1	1.83
Nozzle of Ultrahigh Pressure	1.2	60.0

Table 1: Flow Rate and Pressure Distribution of Pressure Boost Stroke

GRAPHICS



Figure 1: The Assembly Drawing and Flowpaths Section of Fluidic Down-hole Pressure Intensifier



Figure 2: Boosting Theory of Piston-booster



Figure 3: Hydraulic Model of Pressure Boost Stroke



Figure 4: Structure of Fluidic Element and Grid in Section



Figure 5: Stramlines in Section



Figure 6: Pressure Contour



Figure 7: Streamlines of Fluidic Switch in Section





Figure8: Rock-breaking by Jet Erosion in Section





Figure10: The Curved Shape Between Area of Rock-crushing and Pressure of Jet



Figure 11: The Curve of Variation Between Weight of Hard Metal Alloy Nozzle and Time



Figure 12: The Curve of Variation Between Diameter of Hard Metal Alloy Nozzle and Time



Figure13: The Curve of Variation Between Weight of Polycrystalline Diamond Nozzle and Time



Figure14: The Curve of Variation Between Diameters of Polycrystalline Diamond Nozzle and Time



Figure 15: Experiment Facility in Working Condition



Figure 16: Pulsate Pressure Curve



Figure 17: Testing Ground



Figure 18: Reference Data of Field Experiments