IOP Conf. Series: Materials Science and Engineering **283** (2017) 012022 doi:10.1088/1757-899X/283/1/012022

Integrated hydraulic booster/tool string technology for unfreezing of stuck downhole strings in horizontal wells

Q Z Tian[1*]

[1]Petroleum Engineering Technology Research Institute, Sinopec Shengli Oilfield Company, Shandong, China
*E-mail: tianqizhongcs@163.com

Abstract. It is common to use a jarring tool to unfreeze stuck downhole string. However, in a horizontal well, influenced by the friction caused by the deviated section, jarring effect is poor; on the other hand, the forcing point can be located in the horizontal section by a hydraulic booster and the friction can be reduced, but it is time-consuming and easy to break downhole string using a large-tonnage and constant pull force. A hydraulic booster - jar tool string has been developed for unfreezing operation in horizontal wells. The technical solution involves three elements: a two-stage parallel spring cylinder structure for increasing the energy storage capacity of spring accelerators; multiple groups of spring accelerators connected in series to increase the working stroke; a hydraulic booster intensifying jarring force. The integrated unfreezing tool string based on these three elements can effectively overcome the friction caused by a deviated borehole, and thus unfreeze a stuck string with the interaction of the hydraulic booster and the mechanical jar which form an alternatively dynamic load. Experimental results show that the jarring performance parameters of the hydraulic booster-jar unfreezing tool string for the horizontal wells are in accordance with original design requirements. Then field technical parameters were developed based on numerical simulation and experimental data. Field application shows that the hydraulic booster-jar unfreezing tool string is effective to free stuck downhole tools in a horizontal well, and it reduces hook load by 80% and lessens the requirement of workover equipment. This provides a new technology to unfreeze stuck downhole string in a horizontal well.

1. Introduction

At present, available unfreezing methods commonly used in horizontal wells include the following components.

(1) Surface lifting equipment + underground jar tool string [1]. The surface lifting equipment quickly lifts the drill string to generate elastic energy which is stored by the delay mechanism connected to the jar at the bottom of the drill string, and then the instantaneous release of the elastic energy creates a shock to unfreeze the stuck string. However, the elastic energy may be counteracted by the friction in the horizontal wellbore, thus the jarring effect is poor.

(2) Hydraulic anchor + unfreezing tool string. The hydraulic anchor sets the unfreezing tool string against the wall of the casing, then a large-tonnage pull force is applied to the wall between the hydraulic anchor and the fish by the hydraulic booster to free the stuck string. The advantage of the technology is that the pull force applied to the wall of the casing through the anchor protects the upper tubing string from damage, so it is widely used in oil fields. The disadvantage is that the large-tonnage pull force easily forces the stuck string to break or the fish top to crack or deform [2], making more difficult the further fishing operation.

(3) Jar + back-off tool string. First, use the jar to loosen the thread on the fish, and then use the left-handed string to buckle the back-off, thus to unfreeze the stuck string. However, influenced by wellbore frictions, it is difficult to transmit the torque from the surface equipment to the downhole back-off tool [3], and accordingly, the unfreezing result is poor. In order to solve the problems above, hydraulic booster and spring accelerator have been developed. Using these tools, the pull force energy to downhole drill string from ground equipment can be converted into the elastic energy stored in spring accelerators to counteract the horizontal section friction; and under the interaction of hydraulic booster and jar tools, successful unfreezing operations are performed in horizontal wells.

2. Integrated unfreezing tool string

2.1. The tool string structure

The integrated hydraulic booster -jar unfreezing tool string is made up of (from bottom to top) fishing tool + jar + spring accelerator + hydraulic booster + hydraulic anchor + tubing string (figure 1).

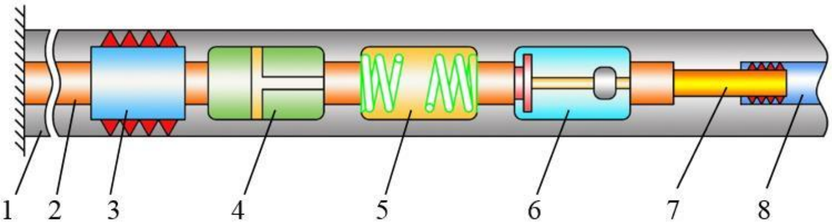

Figure 1. The schematic integrated hydraulic booster -jar unfreezing tool string.
1-Casing; 2-Tubing; 3- Hydraulic anchor; 4- Hydraulic booster; 5- Spring accelerator; 6-Jar; 7-Fishing tool; 8-Fish

2.1.1. Spring accelerator. In the case that a stuck string is in a horizontal section, in order to overcome the friction caused by the deviated borehole, first mechanical energy is converted into elastic potential energy of the spring accelerator by the hydraulic booster, and then the elastic potential energy is converted to kinetic energy of the jar piston, thus to unfreeze the stuck string. The schematic structure of the spring accelerator is shown in figure 2.

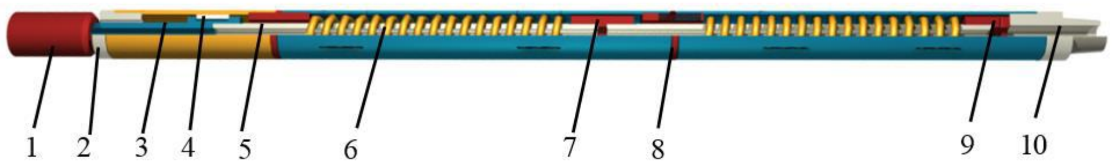

Figure 2. Schematic structure of the spring accelerator.
1 - Top joint; 2- Sleeve; 3-Mandrel; 4-Flat key; 5-Central tube; 6-Spring; 7 - Inner joint; 8-Outer joint; 9-Base; 10-Bottom joint.

Operating principle: The spring accelerator adopts two-stage spring cylinder structure which ensures two groups of springs in a parallel pattern to store elastic energy and thus doubles elastic energy. In addition, to increase the stroke of the spring accelerator and get a long jarring stroke, small single spring accelerators can be connected in series. During an unfreezing operation, the bottom of the spring accelerator is connected to the jar, and the top connected to the booster; after the fishing tool connected to the jar grasps a fish, a large hydraulic pressure is created by ground pumps, and hydraulic anchor on the booster opens and sets against the casing wall; at the same time, the cylinder of the hydraulic booster moves up under the hydraulic force, the booster outer sleeve drives the spring accelerator mandrel up with the bottom joint, and in turn the mandrel drives the base and the inner joint to compress the spring to create elastic energy through the central tube; at this point, the jar enters the delay phase, the elastic potential energy is released instantaneously as the delay mechanism is activated, and the resulting kinetic energy on the jar mandrel is applied to the stuck point.

Table 1 shows the technical parameters of the energy storage spring calculated according to the structure and performance requirements of the spring accelerator.

Table 1. Technical parameters of the energy storage spring.

Material	OD, mm	ID, mm	Free length, mm	Stiffness, $N \cdot mm^{-1}$	Number of coils
55CrSi	99	55	631	153	23

Preset conditions: the single-stage stroke of the spring accelerator is 110 mm, and the total strokes required to complete a shock is 360 mm; to get the length, four groups of spring accelerators are connected in series, with a single spring providing a free length of 631 mm; thus, the total free length of the four groups is 631 mm × 8 = 5048 mm; the elastic coefficient of a spring accelerator is $K_2 = 2K_1$, accordingly the elastic coefficient of four accelerator series is $K_3 = K_2/4 = K_1/2$; after installing, the compressed length is Δx_1 = (631-620) × 4 = 44 mm, the total working stroke Δx_2 = 110 × 4 = 440 mm; as a jarring stroke is 360 mm, then the total spring variation $\Delta x_3 = \Delta x_1 + \Delta x_2 - 360 = 124$ mm.

The initial elastic potential energy is:

$$E_j^{'} = \frac{1}{2}k(\Delta x_1 + \Delta x_2)^2 \tag{1}$$

Substitution of K_3, Δx_1 and Δx_2 into equation (1), yields $E_j^{'} = 8960.292$ J

The final elastic potential energy is:

$$E_j^{"} = \frac{1}{2}k\Delta x_3^{\ 2} \tag{2}$$

Substitution of K_3 and Δx_3 into equation (2), yields $E_j^{"} = 588.132$ J

The converted elastic potential energy is:

$$E_j = E_j^{'} - E_j^{"} \tag{3}$$

Thus, we get E_j=8372.16J

Since the hydraulic booster-jar tool string is in the horizontal section, the variation of its gravity potential energy is not considered. According to the law of conservation of energy, the elastic potential energy is converted to the kinetic energy of the jar mandrel and spring accelerator sleeve and drill pipe, and then creates a shock on the struck point.

The total mass of the jarring acceleration system is:

$$m = m_1 + m_2 + m_3 + 2m_4 \tag{4}$$

where m_1 is the mass of the jar mandrel, kg; m_2 is the mass of the leader of the jar, kg; m_3 is the total mass of the accelerator sleeve, kg; m_4 is the mass of a single drill pipe, kg.

Taking these values (m_1=62 kg, m_2=14.3 kg, m_3=230.8 kg, m_4=138 kg) into equation (4), we get m=583.1 kg.

According to the law of energy conservation, the instantaneous jarring speed is

$$\frac{1}{2}\mathrm{m}v^2 = E_j \tag{5}$$

So E_j=5.36 m/s

According to the momentum theorem,

$$Ft = mv_2 - mv_1 \tag{6}$$

After the shock (which is very short – from 10 to 15 ms) is over, v_2=0, and equation (6) yields:

$$F = -\frac{mv_1}{t} = -312541.6 \text{ N}$$

where the negative symbol indicates that the jarring force is opposite to the direction of the jarring stroke. The instantaneous jarring force to a fish is about 313 kN.

2.1.2. Hydraulic booster. The hydraulic booster is one of the key tools in the integrated unfreezing tool string. Its role is to change the way that a stuck string is shocked by a large-tonnage pull force between the stuck point and the booster by pumping fluid through tubing string [4]. The hydraulic booster can both increase the pull force and stretch the spring accelerator to store more elastic potential energy. The jar has a delay mechanism, which can release the energy instantaneously and apply a shock on the stuck point. Figure 3 shows the schematic structure of the hydraulic booster.

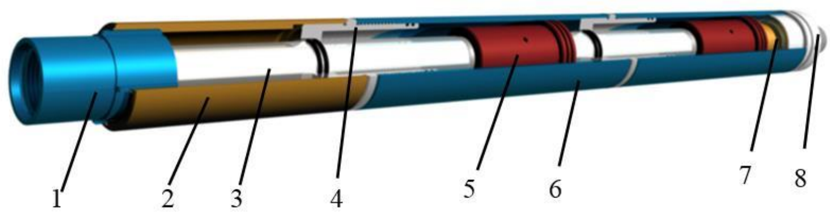

Figure 3. Schematic structure of the hydraulic booster.
1 – Top joint; 2-Top sleeve; 3-Central tube; 4-Connector; 5-Piston; 6-Cylinder liner; 7-Valve seat; 8-Bottom joint

Operating principle: The hydraulic booster consists mainly of a top joint, a central tube, a piston, a cylinder liner, a valve seat, a bottom joint, and other components. When pumping fluid into the tubing, the fluid enters the annulus between the piston and the cylinder liner; because the piston connects to the hydraulic anchor through the central tube and the top joint, and it is away at a relatively fixed distance from the casing, the connector creates an upward pull force under the action of hydraulic pressure [5], which is applied directly to the spring accelerator through the cylinder liner and the bottom joint. The booster cylinder adopts a multi-stage parallel structure, and the maximum can be up to six stages according to required pull force and speed [6].

Technical features: The hydraulic booster changes the way that the stuck string is shocked. The pull force from the ground equipment on the downhole string is converted to the hydraulic pressure in the tubing, and then converted into pull force by the booster and directly applied to the spring accelerator and jar [7]. During unfreezing operation, no friction will be produced between the tubing and the casing wall, as well as no lateral force, so the casing won't be damaged [8]. This is very suitable for unfreezing stuck string by jar or booster in horizontal and highly deviated wells.

According to the structure and performance requirements of the hydraulic booster, the strength of its parts was calculated and verified. The strength verification formula for the parts is referred to the "Mechanical Design Manual" and other relevant information.

As shown in figure 4, the OD-to-ID ratio of the cylinder is $K = \frac{D}{d} = 1.15 \leq 1.2$ (D is the OD and d is the ID), the strength verification is calculated using the thin-walled cylinder theory which assumes that the cylinder is encountered stresses in two directions, and the stress on any section is even: the radial stress $\sigma_\mathrm{r} = 0$, and the circumferential stress is $\sigma_\theta = \frac{P(d+\delta)}{4\delta}$, $\sigma_z = \frac{P(d+\delta)}{2\delta}$. According to the first Strength theory, the theoretical strength formula for the cylinder wall thickness is:

$$P = \frac{2\times\sigma_s\times\delta}{n(d+\delta)} \tag{7}$$

where P is the body compressive strength, MPa; σ_s is the material yield strength, MPa; δ is the wall thickness, mm; d is the ID, mm; n is the safety factor, dimensionless.

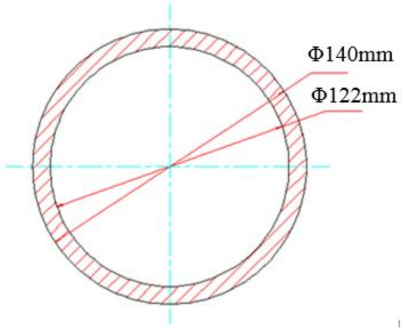

Figure 4. Cross section of the cylinder liner of the hydraulic booster.

All parts are made of 35CrMo steel, which yield strength is 835 MPa and tensile strength is 980 MPa, and safety factor is n=1.25. The internal pressure strength calculated by formula (7) is 91.8 MPa, which is much larger than the highest field pumping pressure, therefore, it meets the strength requirements.

The finite element analysis method was used to simulate the stress distribution on a single cylinder liner of the hydraulic booster under the highest working pressure (25 MPa). The ANSYS 14.0 software was used. The solid 187 unit was selected and the 35CrMo properties include the Young modulus of 2.13 × 105 MPa, Poisson's ratio of 0.286, the mass density of 7870kg/m^3. After meshing (figure 5), a 25 MPa hydraulic load was applied, and the stress was simulated (figure 6).

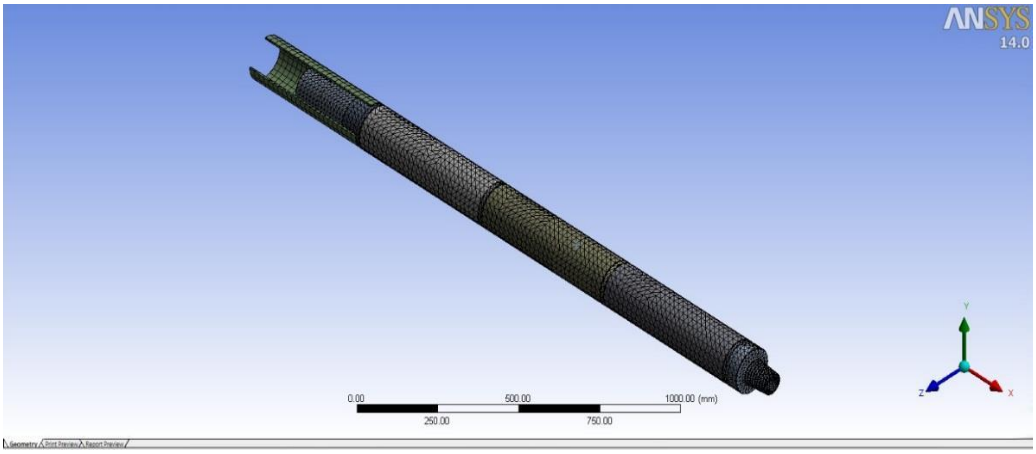

Figure 5. Schematic diagram of finite element meshing of the hydraulic booster.

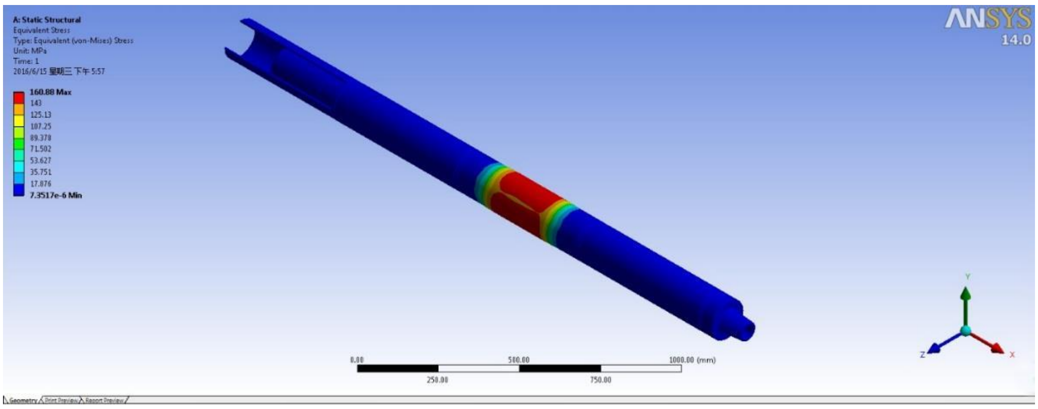

Figure 6. Stress distribution diagram of a single cylinder liner.

IOP Conf. Series: Materials Science and Engineering **283** (2017) 012022 doi:10.1088/1757-899X/283/1/012022

The stress distribution diagram shows that the maximum stress in the cylinder liner is 160.88 MPa, which is much smaller than the yield strength of the material. Therefore, the designed strength satisfies the performance requirement.

Considering field operation, the specifications and technical parameters of the hydraulic booster were determined and listed in table 2.

Table 2. Technical parameters of the hydraulic booster.

Max. OD, *D*, mm	Casing ID, *d*, mm	Rated pressure, P, MPa	Free length, *L*, mm	Rated pull force, *F*, kN
115	121-132	20	900	490
140	150-162	20	900	1000

2.2. Unfreezing principles

First catch the fish with fishing tools, then pump fluid into the tubing to open the hydraulic anchor clutches while the cylinder of the hydraulic booster moves up quickly and drives up the central tube of the spring accelerator. Because of connecting to the delay mechanism of the jar, the outer working sleeve of the spring accelerator is relatively slow, while the central tube compresses the springs in the working sleeve and stores the elastic energy. When the delay mechanism reaches the release chamber, the elastic potential energy is instantly released and converted into kinetic energy of the jar mandrel, which will shock the jarring sleeve and then drive the fishing tools to shock the stuck point. Repeat the procedures until the stuck string is released successfully.

3. Indoor tests

After the completion of the development of the single tools, the performance parameters of the tools were tested on the ground and the results meet the designed requirements. Then downhole simulation test on the entire tool string was carried out. The simulation device and parameters are shown in figure 7 and table 3.

Figure 7. Simulation test device for the horizontal well jarring tool string.
1 –Hydraulic lifting system; 2-Torsion system; 3-T-pipe; 4-Water hose; 5- Tool string

Table 3. Simulation test parameters.

Pre-tightening force, kN	Pumping rate, $m^3 \cdot min^{-1}$	Boosting time, s	Pump pressure, MPa	Delay time, s	Instantaneous jarring force, kN
50	1.2	4	5	23	287

IOP Conf. Series: Materials Science and Engineering **283** (2017) 012022 doi:10.1088/1757-899X/283/1/012022

The downhole simulation test has proved that the technical solution of the hydraulic booster + jar unfreezing string is feasible in horizontal wells, indicating that performance parameters meet the design and can be used under the field test conditions. The field technical parameters of the hydraulic booster + jar unfreezing string are determined based on the numerical simulation results and experimental data (table 4).

Table 4. Field technical parameters of the hydraulic booster + jar unfreezing string.

Casing ID, mm	Pumping rate, $m^3 \cdot min^{-1}$	Pre-tightening force, kN	Downward load, kN	Jarring force. kN
121-159	≥1.0	40-60	0-5	280-300

4. Field test

4.1. Operating procedure

- Run into the unfreezing string which is made up of (from bottom to top): releasing spear + rigid centralizer + drill pipe ×1 + jar + drill pipe ×1 + 4-stage spring accelerator + hydraulic booster + 2-stage hydraulic anchor + tubing string;
- Check the depth of the fish while slowing down the string; pressurize to 40 kN, and insert the spear into the fish cavity, and then slowly lift the string; once the jar is fully open, increase the lifting force to 60 kN. If the stuck string is not released at this moment, connect the mud line, and then test pressure at 25 MPa.
- Boost unfreezing force. Enhance pumping rate in the order from 5 MPa to 10 MPa to 15 MPa and until 20 MPa, and keep the pressure stable for 5 min at each point. Once a sudden pressure drop occurs, there is fluid flowing out from the annulus, and the hook load reduces to the original suspending weight, they indicate that the stuck string has been free [9]. Then stop the pump to release pressure, and after 5 min, unlock the hydraulic anchor and lift the string. During lifting, no increase of the load means the string has been free, then run out of the string and retrieve the fish. If the pump pressure does not drop and the hook load does not change, this means the string is still stuck; then it is necessary to restore the string to original suspending state and reset the jar, be ready to unfreeze the string by hydraulic jarring.
- Hydraulic jarring operation. Lift the string to make the original suspending weight increase to 60 kN, enhance the pump pressure to 10 MPa at the highest rate so that the hydraulic anchor can set against the casing wall [10] while the booster cylinder drives up the center tube of the spring accelerator under the hydraulic action. The delay mechanism in the jar slows down the mandrel and the working cylinder of the spring accelerator connected to the mandrel so that the center tube of the accelerator compresses the spring in the cylinder to store elastic energy. When the hydraulic delay mechanism works, the elastic energy stored in the accelerator will be instantaneously released and converted into kinetic energy of the jar mandrel, and the jarring sleeve will be shocked once and in turn the lower fishing tool to unfreeze the stuck string once.
- Repeat the steps above several times until the stuck string is free; otherwise, repeat step (3) by boosting unfreezing force, or further repeat step (4) by hydraulic jarring until the fish is retrieved and the string is free.

4.2. Application cases

The Zhong14-Ping X well is a horizontal well in the First Field of Gudao Oil Production Plant in Shengli Oilfield, China In order to improve the sand control, the well was completed with a screen liner, and gravel packing was done outside the screen liner. After packing, the packing tool string was stuck. After lifting up by 30-ton load using the workover rig, the tool string was still stuck. Then the string above the safety joint was run out of the wellbore. The fish was ready to be retrieved by the unfreezing process with hydraulic booster and jar. The string parts left in the wellbore and their data are shown in table 5.

Table 5. The string parts left in Zhong 14-Ping-X well.

No.	Tool	Length, m	Depth, m
1	Bottom packing device	2.10	1497.69
2	Tubing sub	1.01	1495.59
3	Centralizer	0.33	1494.58
4	Tubing tub	2.03	1494.25
5	Centralizer	0.33	1492.22
6	Safety joint	0.40	1491.89
7	Setting tool	0.58	1491.49
8	Tubing	54.34	1490.91
9	Packing tool	1.38	1436.57

The unfreezing string is made up of (from bottom to top): Φ76 mm releasing spear + Φ150 mm centralizer + Φ73 mm drill pipe × 1 + jar + Φ73 mm drill pipe × 1 + 4-stage spring accelerator + hydraulic booster + 2-stage hydraulic anchor + Φ88.9 mm tubing string to the wellhead.

After running the string to the stuck point, an attempt was made to free the fish by boosting hydraulic pressure up to 50 ton, but it didn't remove the sand plug. Then the jarring method was used but the plug was still present after trying for 20 times and, finally, the pull force was increased up to 50 ton. After repeating the jarring operation for 40 more times, the string was observed to move up at a small distance at the wellhead, indicating that the plug had been loosened. After increasing the force to 30 ton, the suspending weight was reduced significantly. After repeating the boosting and jarring operations, the sand plug was eventually removed.

5. Conclusions

- The integrated unfreezing technology supported with spring accelerator and the hydraulic booster is effective to unfreeze stuck string in a horizontal well by reducing the friction caused by the deviated wellbore.
- The hydraulic booster-jar unfreezing tool string can unfreeze stuck string through the jarring operation and hydraulically boost the pull force. These two mechanisms worked together to obtain the successful unfreezing result.
- During field operation, to activate the booster to drive the spring accelerator for accumulating elastic energy in a short time, the pump displacement must be higher. However, a hydraulic pressure increase can only lead to a shock and the operation is complicated. Future study will focus on the development of a jarring tool string which can apply a continuous jarring force through ground pumping, thus to improve the jarring effect.

Acknowledgments
The author would like to thank the management of Petroleum Engineering Technology Research Institute for their permission to publish this paper. The author would also like to acknowledge the contribution of the oil well intervention/workover team.

References
[1] Sun R P and Jin D S 1996 New super fishing jar *China Petroleum Machinery* **24(7)** 38-41
[2] Tian M and Wu W H 2008 Improvement and application of hydraulic jar for high-pressure ultra-deep well *China Petroleum Machinery* **36(8)** 81-3
[3] Zhou J Q, Zhang G T, Li D Y, *et al* 2009 Development and application of the fully hydraulic while-drilling bumper sub China Petroleum Machinery **37(9)** 89-91

[4] Zhang G T and Long J Q 2009 Application and improvement of a hydraulic downhole pulling tool Oil Field Equipment **38(2)** 75-9
[5] Guo J G and Zhang H Q 2004 A new hydraulic downhole fishing tool with augmenter for special wells China Petroleum Machinery **32(8)** 37-9
[6] Wang L L, Jiang Z S, Zhang J Z, *et al* 2012 Study on unfreezing and fishing technology for horizontal wells Oil Field Equipment **41(9)** 64-8
[7] Kong L W 2013 Reinforced stick-freeing and fishing techniques of the string pipe of the horizontal well Petroleum Geology & Oilfield Development in Daqing **32(3)** 93-6
[8] Wang B and Kong C L 2013 Unfreezing and fishing techniques for horizontal wells Petroleum Geology & Oilfield Development in Daqing **32(4)** 94-7
[9] Li J Y, Li M Z, Du B G, *et al* 2011 Stress analysis and strength check for hydraulic force increasing stuck-releasing strings Oil Drilling & Production Technology **33(6)** 49-52
[10] Fu J H, Luo J and Li C Y 2008 Workover operation technology for horizontal wells in China Drilling & Production Technology **31(6)** 91-3