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Full Length Research Paper

Systematic approach for improving performance of progressive cavity pumping systems in a deep heavy oil reservoir

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A pragmatic and systematic technique has been developed to improve performance of the progressive cavity pumping system in a deep heavy oil reservoir where oil produces together with sand in an unconsolidated formation. More specifically, tapered thread has first been used to replace the conventional ones for strengthening the resistive torque of the entire string. The rotary anchor equipped with scalable slips is then adopted to not only avoid the tubing bend generally resulting from the compressed setting anchor, but also be easily retracted at the bottomhole even where sand is accumulated. A frequency converter is used to control the rotating speed, which allows the pump speed to be adjusted accordingly without powering off the motor. In addition, an upright notch intake is adopted to set below the orientation spool of the pump for mitigating sand accumulation. It has been found from over 200 wells that the newly developed technique can be used to greatly improve performance of the progressive cavity pumping system for increasing oil production from deep heavy oil reservoirs by significantly extending the life of the rod string.

Key words: Progressive cavity pumping (PCP), deep heavy oil reservoir, performance improvement, tapered thread.

INTRODUCTION

Down hole progressing cavity pump (PCP) has gained its popularity in pumping abrasive fluids (heavy oil) together with sand in a relatively shallow reservoir, minimizing effect of sand and free gas (Dunn et al., 1995). In an unconsolidated sandstone heavy oil reservoir, the PCP system allows continuous production of the massively discharged sand along with oil, improving the formation permeability near wellbore and thus well productivity (Chugh et al., 2000). As for a deep heavy oil reservoir, where oil produces together with sand in an unconsolidated formation, however, the conventional PCP system has found its limitations due to a lower fluid level, which leads to a larger torque and heavier load as both the pump setting depth and forces imposed on the rod string are increased substantially (Lea et al., 1988; Noonan, 2008; Saveth et al., 1989). Therefore, it is of practical and fundamental importance to improve the reliability and performance of the traditional PCP system in a deep and unconsolidated heavy oil reservoir.

The down hole PCP system consists of an eccentrically rotating worm-shaped rotor inside of a flexible stator. The rotor is driven by a high-strength steel rod string inside the tubing, which is rotated by a motor-driven surface unit. In addition to the eccentricity of rotator, cross-sectional areas of rotator, and stator pitch, the PCP head lift is also dependent on the pump stages. As for the same delivery capacity, increasing eccentricity of rotator can reduce either the cross-sectional area of rotator or the pitch of the stator. Increasing eccentricity of rotator advisably can improve the sealing between the rotator and the stator, raise head lift of single stage pump, reduce friction between them and increase sand flux. As the head lift is increased, the rod string undergoes a substantial increase in both torque and load. The twist-off can be resulted from C the eccentric movement of rotator

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and transversal vibration of the rod (Yan et al., 2008). In addition, a tubing anchor is required for a PCP system to prevent tubing from being screwed off, which includes hydraulic anchor, tensile anchor, compression anchor, plate-turnover anchor and rotary anchor. At present, the widely-used anchor on the conventional PCP systems is the compression anchor, which requires a load of 4,000 to 8,000 kg imposed by the tubing itself to set the anchor. Such a large working load may cause a portion of the tubing to be bended to some extent and consequently result in the eccentrical wears on the tubing (Zhu et al., 1999). Since both the slips and support slide are located outside of the compression anchor, the slips will be unable to move and shrink back for grapple removal, once buried by the producing sand.

Initially, the sucker rod string used for the PCP system is the same as that for the conventional beam pumping system, though it can endure more tension but less torque. Hollow rods are found to be more resistant to torque than the solid rods, but the collar remains the weakest point due to its wall thickness. Even wall thickness of the collar can be increased, the pump setting depth remains shallow. When the oil-bearing formation is close to 1300 m or deeper, it is easier to cause the rod strings broken and twist-off due to a larger vertical load and torque. This is the key element that limits the traditional PCP system to be applicable and reliable in a deep heavy oil reservoir where oil produces together with sand in an unconsolidated formation. In order to allow fluid production from a deep formation, various attempts have been made to modify the rod strings (for example, the continuous sucker rod and the tapered-thread sucker rod) for the PCP system (Hopkins et al., 2009; Telli et al., 2009). With no collars, the continuous sucker rod can be used to only enhance pumping performance, but also avoid twist-off caused by its reversed movement when being shut down. In addition to the constraints of the maximum diameter allowing for the rod-string, the sophisticated manufacturing and workover requirements limit its extensive application. Compared to the conventional PCP system, the tapered-thread sucker rod adopts the tapered thread to not only bear a greater pre-tightened load without causing thread slipping and shows good sealing performance, but also endure a greater axial load and torque.

In this paper, a pragmatic and efficient technique has been developed to improve performance of the PCP system in a deep heavy oil reservoir where oil produces together with sand in an unconsolidated formation. More specifically, tapered thread is adopted to strengthen the resistive torque of the entire string, while the rotary anchor equipped with scalable slips is employed to avoid both the tubing bend and difficulty in retrieving it when being buried with sand. Then, a frequency converter is introduced to smoothly adjust and maintain production without shutting off the well, while an upright notch intake is adopted to set below the orientation spool of the pump for mitigating sand accumulation. Case studies are discussed and analyzed to demonstrate the successful application of the newly proposed technique for improving performance of PCP systems in deep unconsolidated formations.

FIELD BACKGROUND

The Yuhuangmiao reservoir is located in the Shengli Oilfield where the Donger formation is the main production zone. The payzone is located at depth of 1430.0 to 1495.0 m with average air absolute permeability of 370 md and reservoir temperature of 50 to 57°C. The oil density and viscosity are measured to be 969.9 to 993.6 kg/m^3 and 1331 to 5606 mPa·s at 50°C, respectively. The crude oil contains less than 5% of asphaltene but more than 30% of colloids. The median grain diameter for the produced sand is found to be 0.129 mm. The average radius for the pore throat is found to be 11.97 μm, while the clay content is 10.7%.

The traditional water sensitivity test (Figure 1) has been performed for the Yuhuangmiao reservoir. Obviously, as seen in Figure 1, the permeability is significantly decreased as more water is injected into the core sample taken out from the reservoir. This means that this is a reservoir with strong water sensitivity. Therefore, no water injection has been made available in the reservoir even for the purpose of pressure maintenance due to its strong water sensitivity.

Prior to adopting the modified PCP systems, the pump setting depth is about 1000 m. As time proceeds, continuous drop of the fluid level results in increasing the pump depth so that the rod string is broken down or twisted off more frequently as its load and torque has been substantially increased. Meanwhile, fluid production about 3 m^3/d is discontinued because the well is plugged by the sand coming out from the formation. Even though some wells were treated with chemical methods for sand control, they still cannot maintain the minimum production level and the fluid production falls below 1 m^3/d.

METHODOLOGY

In the past few years, the modified PCP systems presented in this paper have been used to increase oil production for over 200 wells in selected reservoirs in the Shengli Oilfield. The general methodology can be briefly summarized as follows;

1. The improved rod string with the tapered thread is used to enhance its torsion strength,
2. The rotary anchor is adopted to alleviate the problem of tubing bend and to be easily retracted while being buried by sand,
3. A frequency converter is used to control the power supply frequency of the asynchronous motor for achieving variable speed without shutdown and avoiding pressure fluctuation and sand accumulation,
4. An upright notch intake is adopted to set below the orientation spool of the pump for mitigating sand accumulation. Such pump

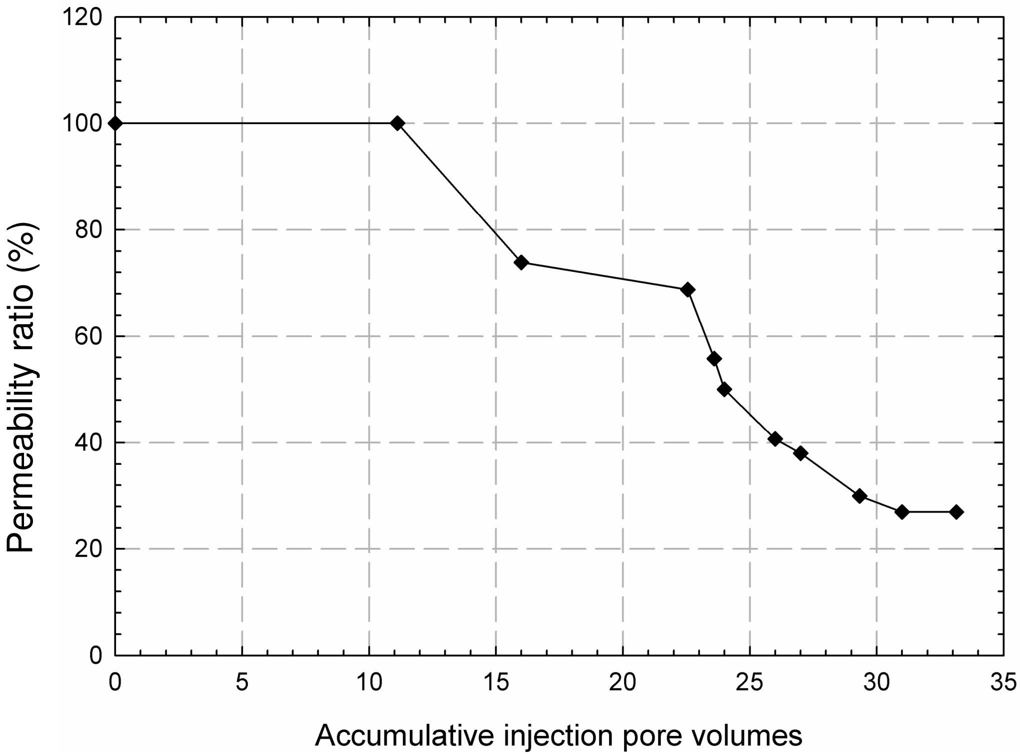

Figure 1. Ratio of permeability due to water injection to its original permeability as a function of accumulative pore volume of the injected water during a conventional water sensitivity test.

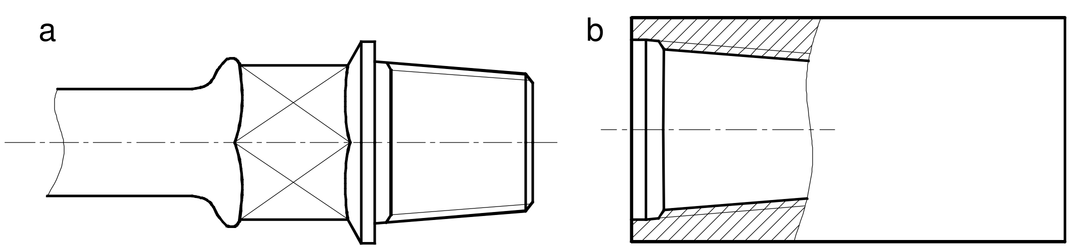

Figure 2. A schematic of tapered thread: (a) Joint, and (b) coupling.

intake is positioned at least 1 m below the bottom of the perforation zone to timely discharge the producing fluids and sand, and

5. An oil storage tank is used at the wellhead to reduce the back-pressure and separate the sand out from the producing fluids prior to flowing in the surface pipeline.

Tapered thread

A schematic of the tapered thread is depicted in Figure 2. Its wall thickness at the inlet is similar to that of the conventional collar, while the wall thickness at the heel is increased to significantly enhance its torsion strength. Furthermore, the break-out torque is found to increase as the make-up torque is increased, while the ratio of the break-out torque to the make-up torque is measured to be 0.8 (Figure 3). In this way, such a high torque ratio implies that the rod strings will not be easily unscrewed and twisted off while being rotated reversely. Compared to the conventional rod string, there exists no significant difference for the tapered one. The tapered rod string can be hollow in the centre, while diameter of the rod string can be manufactured to be 25 mm or larger.

Pump intake

As for pumping fluids out from a deep formation with a PCP system, it is necessary to properly set the pump intake. In practice, an orientation spool is installed at the bottom of the PCP system to mitigate sand movement into the pump. It is found from field applications that an upright notch tailpipe provides a better solution for the pump intake. More specifically, the orientation spool is extended to set the pump intake between the locating pin and pump. Four to six rectangular vertical notches are devised on the locating pin with a width of 10 mm and a height of 150 to 200 mm.

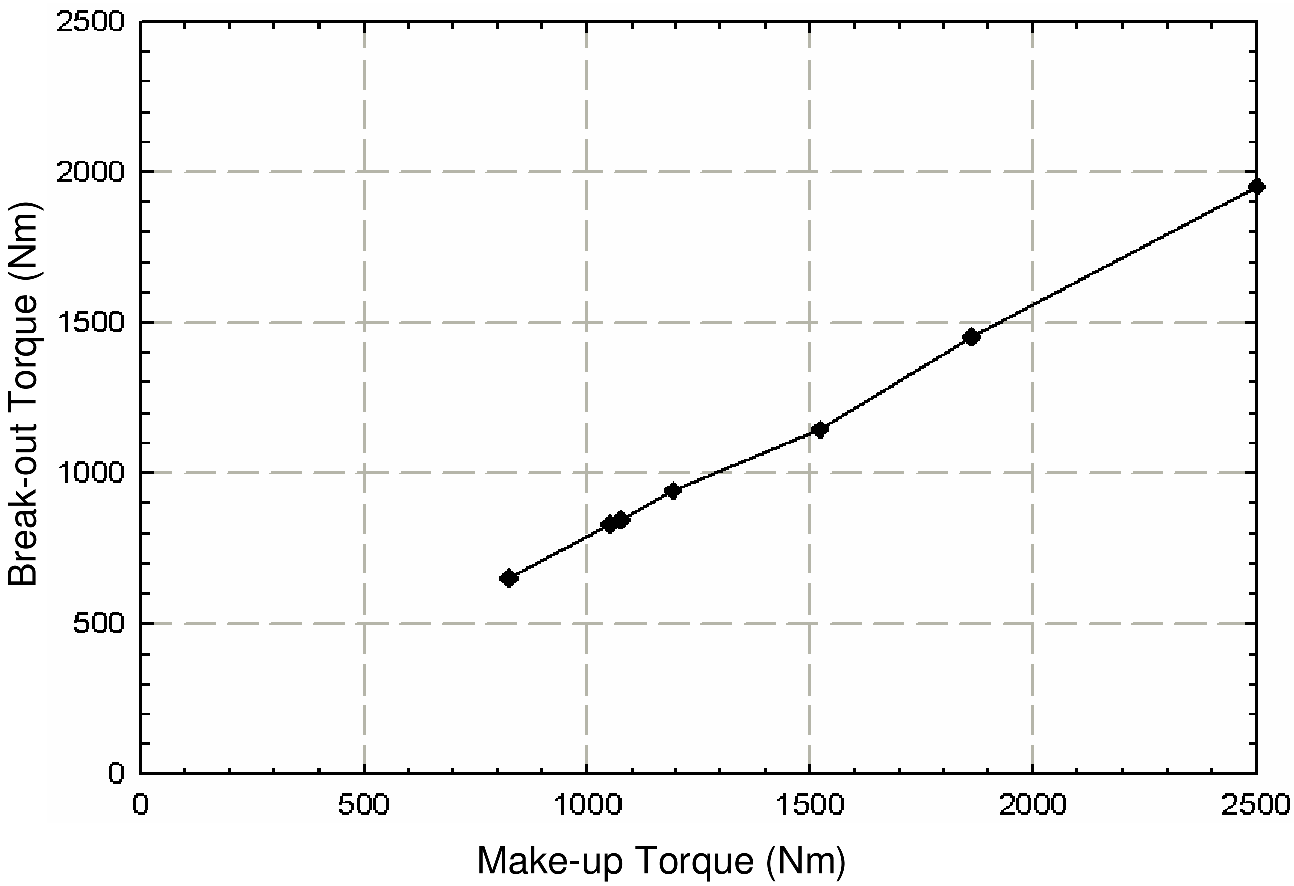

Figure 3. Measured make-up and break-out torques.

A schematic of the modified PCP system together with pump intake configuration is plotted in Figure 4a. In general, as for the conventional PCP system, the tailpipe is placed about the payzone to allow formation fluids to be either sucked into the pump intake at the bottom of the tailpipe, or to flow into the tailpipe via the liner right above. With such a conventional configuration, the sand-carrying oil stream moves much slower in the casing than in the tubing and thus the sand tends to deposit and fill up the pocket.

In general, the pump intake is set at least 1 m below the bottom of the perforation zone to allow quick discharge of the sand-carrying oil stream. Otherwise, the sand deposited and accumulated in the pocket will restrain the flow of oil and sand and may eventually kill the well. It should also be noted that a storage tank must be used to effectively reduce the backpressure and separate most of the sand at the wellhead before the oil is pumped into the surface lines.

Pump anchoring

As for a deep formation, the rotary anchor has been found to be a better choice for the PCP systems. The rotary anchor that is installed at the bottom of the PCP system is composed of an anchoring body, plate-turnover slips and a centralizer. When the pump rotator is rotating to clockwise drive, the pump case and the anchor, the plate-turnover slips turn over and roll out to anchor on the casing by the friction between the plate-turnover slips and the casing (Figure 4b). When the tubing is pulled out and rotated counter-clockwise during workover, the plate-turnover slips move back to release the anchor (Figure 4c). Since the slides are located inside the anchor, the slips can be retracted smoothly to reduce the risk of being unable to pull out the pipe strings whenever the tubing anchor is buried by sand. Also, no vertical setting force is required for the anchoring; the tubing bend can be prevented to some extent.

Frequency converter

The major purpose of using a frequency converter is to control the power supply frequency of the electric motor, adjust variable speed continuously and thus maintain stable production (Boyles et al., 2005). In addition, the frequency converter can be used to implement soft starting on the PCP system and prevent the sucker rods from being broken abruptly with the oversized torque. Once the PCP system is initiated, the rod string undergoes a large torque at the very beginning and then remains almost constant after the rotation speed achieves its stable value (Wang et al., 2003), while torque is slightly increased as the rotating speed (Wang et al., 2008). In this way, the output torque from the asynchronous motor should remain constant all the time, though its rotating speed is changed. As for a conventional asynchronous motor, its torque is proportional to the frequency and voltage. Therefore, a frequency converter is used to ensure that the output torque from the motor is increased at the beginning and subsequently remains almost constant during the stable period. It is found from field applications that the motor should be operated in a range of 70 to 100% of its prorated capacity by reasonably adjusting the compatible

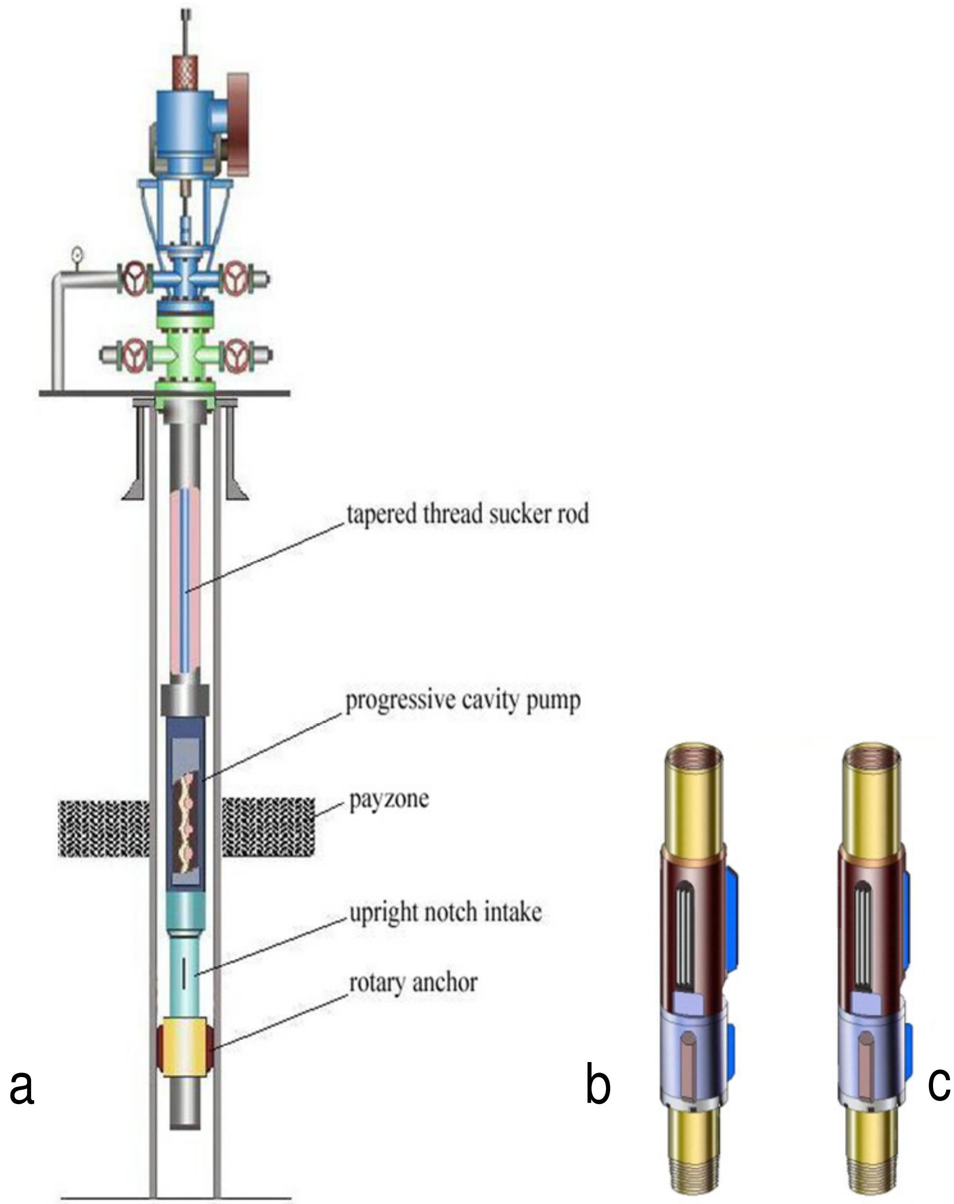

Figure 4. (a) Schematic of the modified PCP system together with pump intake configuration: (b) Rotary anchor in operational state, and (c) Rotary anchor in idle state.

relationship among the prorated rotating speed, gearbox speed and converter frequency.

RESULTS AND DISCUSSION

In this paper, Wells X7-14, X7-13 and X9-16 are presented as an example out of over 200 PCP applications in the Shengli Oilfield. Figure 5 shows the produced fluids (water-cut is about 3%) as a function of time for Well X7-14. Prior to adopting the modified PCP systems, the well produces about 1.0 m^3/d and cannot maintain this rate on a regular basis. The production rate is increased up to 3.0 m^3/d and peaked at 8.6 m^3/d after the modified PCP system has been adopted. The fluctuation in production rate is mainly due to adjustment of the rotating speed. As can be seen from Figure 5, the well stops working after 172 days due to the broken rod-string other than the collar. Subsequently, it continues producing once the broken rod-string has been replaced.

The corresponding sand production for Well X7-14 is plotted in Figure 6. The sand cut is increased to 16.0% at the initial stage, then gradually dropped to below 0.5% and increased to over 16.0% after three months. This is ascribed to the fact that fine sand is produced at the initial stage and reaches the first peak after the modified PCP

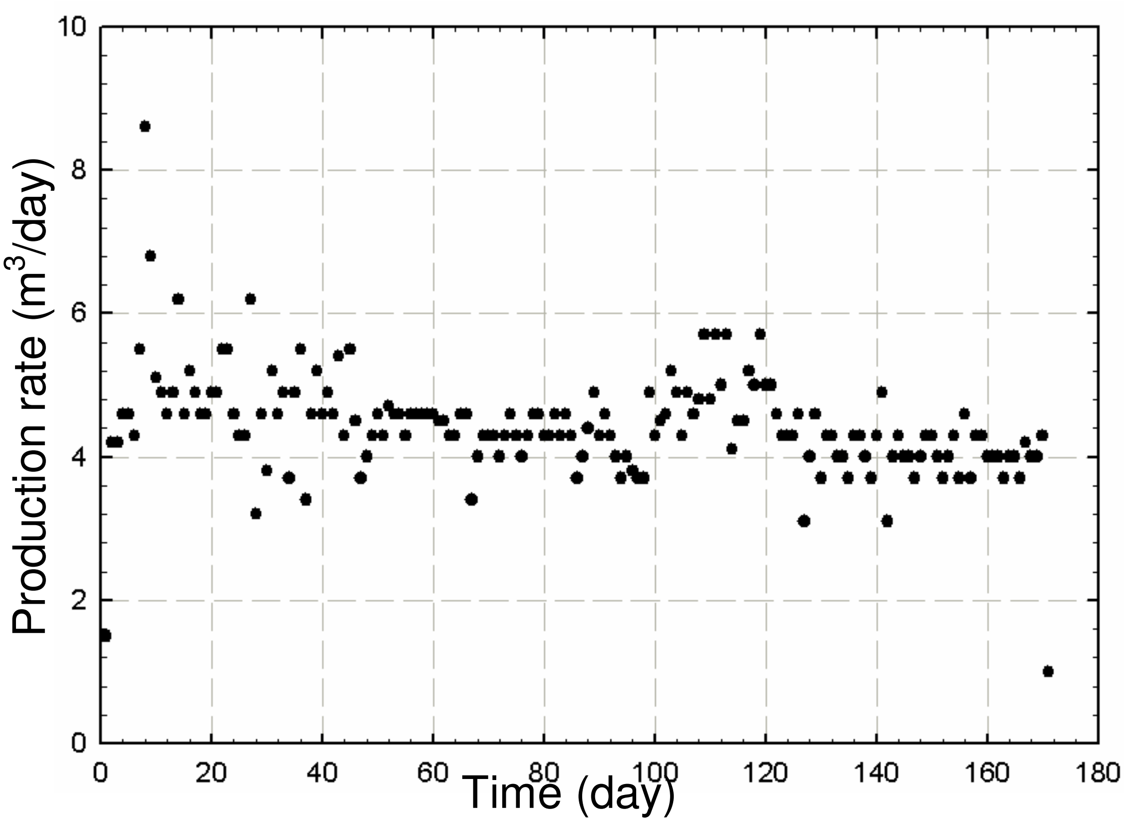

Figure 5. Well productions as a function of time for well X7-14.

system is implemented and then remains relatively low.

During this period, the fine sand is coming out continuously from the formation, while the skeletal sand near wellbore is losing support due to continuous production of fluids and fine sand and merges into the production stream at 105 days. The second sanding peak is shortly achieved and then disappears once most of the unconsolidated skeletal sand has been produced and remains relatively low again. It should be noted that this pilot well has been produced continuously for 172 days without interruption due to power outrage. In this way, the second sanding peak is not resulted from pressure fluctuation due to the interrupted production.

As shown in Figure 7, the production fluid level has risen above 400 m after the well keeps producing more than 20 days. Then, the production liquid level remains stable for 70 days and subsequently drops to its original level. This is mainly ascribed to the fact that the increased fluid production increases sand production as well and thus the produced sand blocks the formation and reduces the fluid production, leading to a lower fluid level. The second sanding peak occurs almost simultaneously with the peak of the dynamic fluid level.

As shown in Table 1, Wells X7-13 and X9-16 have shown positive response since the newly developed technique has been implemented. As for Well X7-13, the first attempt failed after 9 days with a production rate of 5.78 m^3/d due to the fact that the pump capacity is too large and over-pumps fluids from the wellbore, which cannot be timely and sufficiently supplied by the formation. Subsequently, a small pump is used and the well produces much longer, though fluid production is decreased to 2.78 m^3/d.

As for Well X9-16, the tailpipe is designed to position above the perforation zone about 80 m to examine whether the modified PCP systems can be used to remove the accumulated sand. It is found that the production shows positive response at the beginning but declines gradually after a certain period. This is because the sand started moving slower between the payzone and the tailpipe, then accumulated inside the casing to reduce the production. As for the well with sand production, the tailpipe will be buried by the produced sand if it is placed below the payzone. If the well has a deep pocket, the tailpipe should be placed above the payzone to postpone the aforementioned problem and extend the well life. It is worthwhile noting that, for a well with low production, the tailpipe should be placed below the perforated section to facilitate removing sand more easily.

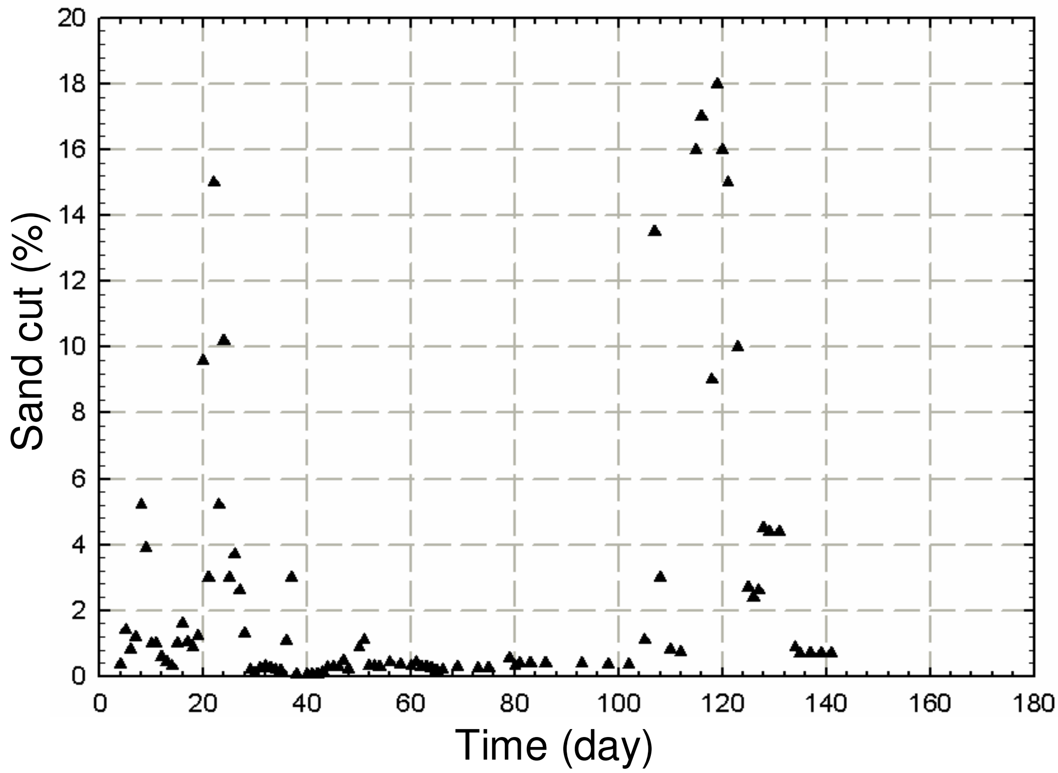

Figure 6. Produced sand cut as a function of time for Well X7-14.

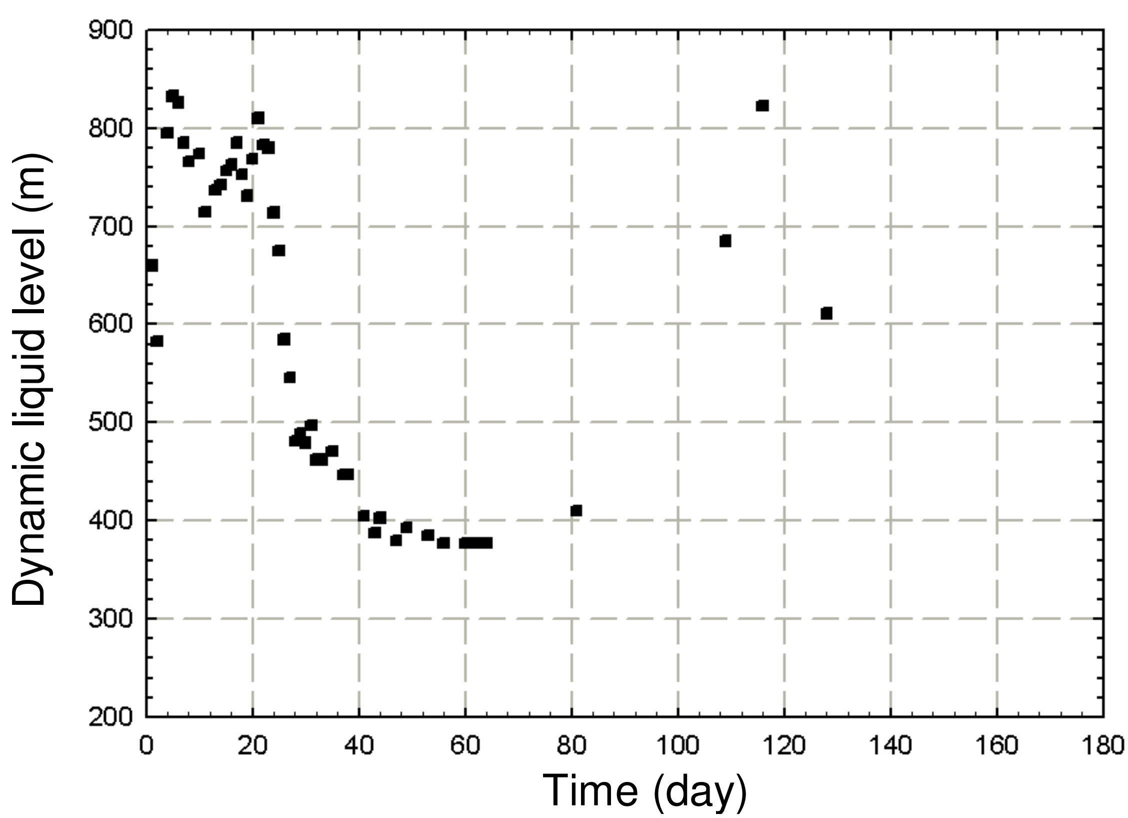

Figure 7. Producing fluid level as a function of time for well X7-14.

Table 1. Production performance for pilot wells.

Well name	Reservoir depth (m)	Test number	Tailpipe depth (m)	Production rate (m^3/d)	Pump capacity (ml/r)
X7-14	1427.8 to 1430.0	1	1437.9	4.43	50
X7-13	1433.0 to 1435.8	1	1444.6	5.78	60
		2	1437.1	2.78	50
X19-6	1480.0 to 1484.0	1	1402.0	9.02	120

Conclusions

In this paper, a pragmatic and systematic technique has been developed to significantly improve performance of the progressive cavity pumping system in a deep and unconsolidated heavy oil reservoir. The rod string is strengthened with the tapered thread for its torsion strength, while the rotary anchor is adopted to alleviate the problem of tubing bend and to easily be removed while being buried by sand. In addition, a frequency converter is used to control the power supply frequency of the asynchronous motor for achieving variable speed without shutdown, while an upright notch intake is adopted to set below the orientation spool of the pump for mitigating sand accumulation. The pump intake should be positioned at least 1 m below the bottom of the perforation zone to timely discharge the producing fluids and sand. It is found from over 200 wells that the newly developed technique can be used to produce heavy oil from a deep and unconsolidated formation in a cost-effective manner.

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