World's First Metal PCP SAGD Field Test Shows Promising Artificial-Lift Technology for Heavy-Oil Hot Production: Joslyn Field Case

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Abstract
Finding a reliable artificial lift pumping system for heavy oil thermal recovery has been a challenge mainly due to the high operating temperatures (>150 °C). Available options such as Rod Pumps and Electrical Submersible Pumps (ESP), which are well proven in the industry, are not particularly well suited to thermal production. While Rod Pumps offer high temperature service, they are limited in the flowrate they can deliver. ESPs on the other hand, can handle high volumes of low viscosity fluids, but are still limited in terms of maximum operating temperature.

Progressing Cavity Pumps (PCP), with elastomeric stator, is economic to run and have done well in heavy oil cold production. These elastomers are however limited in temperature (<150 °C). Through research work conducted by PCM and TOTAL, Metal PCP technology has been developed to meet the high temperature requirement of SAGD and other thermal recovery processes. Three models of the Metal PCP are now available to cover a wide range of flow rates for heavy oil production.

This paper presents an update on the Metal PCP development and the results of the world’s first SAGD field trial of this type of pump currently on-going in Canada in the Joslyn field. Field performance data are discussed comparing high temperature ESP and metal PCP in actual LP-SAGD conditions.

Four SAGD well pairs were initially equipped with high temperature ESP. Another well pair was equipped with metal PCP. This well has been running since mid October 2006 without problems, in spite of low pressure at pump intake, close to steam flashing conditions. Production rate reached 200m³/d of liquid at 340rpm, giving a volumetric efficiency of 53%. Intake temperature is 160°C due to the LP-SAGD condition of the field. However, this pump is rated up to 350°C.

This first field trial shows the metal PCP as a promising artificial lift technology for hot production. Following this encouraging trial, a second metal PCP has been installed with success in the same field and more installations were decided eventually. Thus, all ESP initially installed were replaced by PCP and nine wells are producing with Metal PCPs currently.

Introduction
Recovery of the world’s huge reserve of extra heavy oil (mainly found in the oil sands of Canada and Venezuela) by thermal processes have been on the increase thanks to the high oil price. Key to this recovery process is artificial lift, which is required due to the very high density and viscosity of the crude and relatively low reservoir pressures. Although gas-lift remains an artificial lift option when high-pressure gas is available, pumping techniques are more popular due to their relatively higher efficiency and ability to generate more head at surface for delivery to treating plant.

The main challenge however with hot pumping is the rather high temperatures often required (up to 260°C for SAGD and 350°C for Cyclic Steam Stimulation (CSS)).

The dominant pumping technologies available are Beam/Jack Pumps, Electric Submersible Pumps (ESP) and Elastomer Progressing Cavity Pumps. But all these pumps have their peculiar limitations for hot production: while Beam Pumps offer high temperature service, they are limited in the flowrate they can deliver. ESPs on the other hand, can handle high volumes of low viscosity fluids, but are still limited in terms of maximum operating temperature. For the PCP, the limitation is operating temperature of the elastomer (maximum 150°C).

Through research work conducted by PCM and TOTAL, Metal PCP technology has been developed using hydroforming technology to meet the high temperature requirement of SAGD and other thermal recovery processes. This paper presents the world’s first SAGD field trial of this type of pump in Canada in the Joslyn field and compares their operating performance to high temperature ESP.

Metal PCP Description
PCPs are known for their simplicity of design and operation. The heart of the pump is composed of two parts: the stator and the rotor (see Figure 1). The stator has dual helical
profile while the rotor (which rotates inside the stator) has a single helical profile designed to mate the stator profile. The rotating action of the rotor (sitting inside the stator) creates progressing cavities from bottom displacing the fluid through each successive cavity and hence the pumping action. PCPs are non-pulsating pumps and will deliver a constant flow rate for a given rpm of the rotor.

In the conventional elastomer PCP as shown in Figure 2, the part of the stator with the helical profile is made of elastomer and is glued to an external metallic tube. The rotor fits the stator with negative clearance.

For the Metal PCP, the stator is fully metallic and hence able to withstand very high temperature. The metallic helical profile is produced by hydro-forming as depicted in Figure 3. The stator is composed by 3 elements of 9 ft long welded together. Here, rotor fits the stator with positive clearance. Both are specially coated for high temperature and wear resistance, but the rotor serves as a sacrificial element.

Figure 4 illustrates a typical Rod Driven (RD) PCP assembly as set into a well. The stator is usually run first with the production string. The rotor run thereafter and set into the stator. It is connected to drive head at surface with either standard sucker rod string, continuous (coiled) rod or hollow rod string.

Advantages of the metal PCP are the following:
- Easy flowrate control (proportional to RPM)
- Easy to install, similar to conventional PCP
- High operating temperature range (up to 350°C)
- Accept low or high viscosities
- Low NPSH i.e. operates with low bottom hole pressure
- Non shearing and no formation of emulsions
- Easy initial start-up at higher viscosities

The metal PCP is designed presently to have:
- A life time of one year minimum (8000 h)
- Ability to handle sand contained in oil (up to 5%)

**Development Status**

Research effort for Metal PCP development through hydro-forming technology was launched in the mid 1990's by PCM and TOTAL. Several processes were tested for developing a full metallic stator. Only the hydro-forming process was successful in term of industrialization, performances and cost. By 2005, two industrial prototypes were produced and bench tested in hot conditions at the CERT, one of TOTAL research centers located in Gonfreville, France. The tests comprised:
- Performance tests at different RPM (max 400 rpm), delta P (max 135 bars) and temperature (max 350°C).
- Endurance test at 150°C at maximum operating RPM (400 rpm) & delta P (130 bar) for six weeks

The overall efficiency of the PCP is defined by the following relation:

\[ \eta_{overall} = \frac{\text{hydraulic power delivered to fluid}}{\text{mechanical power at pump shaft}} = \frac{Q \cdot \Delta P}{T \cdot \omega} \]

Even with the first industrial prototypes, the bench tests showed encouraging results, with overall efficiency reaching 65% as shown in Figure 11 (details of the bench test have been presented in a previous SPE paper (see in References SPE 97796)).

It also confirmed one of the strengths of the pump, namely a broad viscosity handling capability, which is well-known as an issue for beam pump, and also with ESP as it is discussed in paragraph dedicated to pump performance evaluation hereafter. As shown in Figure 11, for high viscosity, the metal PCP overall efficiency is not very sensitive to delta-P but improves with RPM. For lower viscosity (high temperature), the overall efficiency decreases with increasing delta-P due to internal fluid slippage but this is strongly improved by higher RPM. These tendencies can be observed on the plots of Figure 8 to Figure 10 as well.

Abrasion resistance testing has also been performed in CETIM (a french mechanical engineering centre) in Nantes, France with various coatings on both rotor and stator, leading to a satisfactory industrial solution.

Following these performance and abrasion tests, some improvements have been made in the manufacturing process and the thickness of coatings, providing superior performance and resistance.

Since 2006, three models of the metal PCP are available to cover a wide range of flow rates for heavy oil production. They are the 400MET1000, 550MET750 and the 1000MET500. The first number gives the maximum rate in m³/d at zero head at 500 rpm, while the second number gives the nominal head capacity in meters of water equivalent. The pumps are rated to 350°C.

Presently, twenty (20) metal/metal PCP have been installed in wells under CSS and SAGD. Out of these, four of them failed, one after 6500 hours of operations and the other three prematurely. The failure analysis indicated that the unbalanced movement of the rod string contributed to the fatigue failure.

**Joslyn Field Trial**

The Joslyn Lease is a very shallow (<100mTDV) low pressure oil sands field located in the highly prolific Athabasca oil sands of Alberta, Canada. Crude oil API is 8° with viscosity around 1.7 million cp at virgin reservoir conditions (see on Figure 7 typical crude viscosity versus temperature). In a dedicated area of the lease, SAGD or Steam Assisted Gravity Drainage is used to produce this bitumen through horizontal well pairs. Injected steam heats up the bitumen, which then flows towards the production well underneath.

SAGD production (Phase 1) at Joslyn started in September 2004 with a pilot well pair initially equipped with a Beam Pump that was replaced a few months later with an ESP due to capacity limitations.

For Phase 2 of the Project, 17 additional well pairs were drilled in 2006. The first three well pairs to come on stream in September 2006 were equipped with ESPs. During that time, a fourth well (well#A) was converted to SAGD production using the first Metal PCP. A few months later, following an ESP failure in one of the three wells running with ESP, a second Metal PCP was installed in this well (Well#B). Currently out of the 10 wells on production, nine are
producing with Metal PCPs (including the initial wells where the ESPs have eventually been replaced with Metal PCPs) and one well with high temperature elastomer PCP. Figure 5 shows one of Joslyn wells pads equipped with metal PCPs while Figure 6 shows the typical drive head installed on top of Xmas Tree of these wells. All the pumped wells are equipped with topside and downhole instrumentation in order to get real time well and pump performance data.

This paper specifically focuses on the performance of the first two Metal PCPs in well#A and well#B.

First Metal PCP in well #A

This first pump model was a 550MET750, with a theoretical capacity of 1.1 m³/d/rpm. PCP was landed at 327m MD at an inclination of 86° with 4½” production tubing. A top drive system was used with 1.9”OD Tenaris hollow rods for motorization.

The PCP started producing mid-October 2006 at 150 rpm. Initial volumetric efficiency was about 55%. During this start-up phase of the SAGD well pair, downhole temperature was below 120°C and bitumen viscosity generated some resistance to the flow. It is during that period that the lowest intake pressure at the pump was seen at 440 kPa(g). With the increase of pressure communication between Injector and Producer, pump intake pressure gradually increased as well and pump speed was ramped up in parallel from 150 rpm to 340 rpm. Bottom hole temperature rose to ~160°C. Pump volumetric efficiency remained relatively constant around 45 to 50%, but was becoming very sensitive to the bottom hole temperature above 160°C. About 5.5 months after start up, pump efficiency seemed to drop slightly to about 40% and pump speed was increased to 350 rpm and then 360 rpm to compensate. This speed was deemed to be the maximum allowable speed in order to avoid pump vibration problems. At the time of writing, this 550MET750 PCP is running at 360 rpm with a 35% volumetric efficiency. This pump has been running for 9 months with almost no downtime.

The performance of this pump has exceeded expectation, being the first installation. Pump speed has been increased to ascertain maximum rpm limits in relation to wear and overall run life.

Second Metal PCP in well #B

Well#B was first started up with an ESP and produced about 2.5 months before the ESP failed. During this initial phase, it proved difficult to keep the ESP running continuously and impossible to increase the total flowrate above 50 m³/d. This ESP was oversized compared to the initial well production rate and it was working at the very low range of its envelope. Additionally it is believed that the strong contrast of viscosity of the produced fluid and the limited capabilities of ESPs to handle erratic inflow were the main reasons for the poor performance of the ESP. However, these are the typical well conditions on production start-up and are even more acute at Joslyn due to the limited achievable warm-up of the reservoir prior to initiating production and the unavoidable cooling down of the well bore during pump installation. The other two wells with ESPs showed the same production problems.

When the ESP failed, opportunity was taken to try another Metal PCP to see if a PCP could solve these production issues. This second pump model was a 400MET1000, with a theoretical capacity of 0.8 m³/d/rpm. The PCP was landed at 309 m MD at an inclination of 88° with 4½” production tubing. A top drive system was used with 1.9”OD Tenaris hollow rods for motorization.

This PCP started producing mid-February 2007 and pump speed was quickly ramped up to 155 rpm and then gradually to 210 rpm. Pump volumetric efficiency was consistently very high at about 80%. Liquid flowrate reached 150 m³/d and bottom hole temperature 145°C with a pump intake pressure of about 800 kPa(g).

About 2 months after start-up, pump efficiency seemed to drop significantly to about 45 to 50%. However well continued to warm-up to 164°C at the pump. At the time of writing, this 400MET1000 PCP is running at 330 rpm with a 45% volumetric efficiency. This pump has been running for 5 months with almost no downtime.

Pump Performance Evaluation

The field trial of the first Metal PCP in a low pressure SAGD operation has demonstrated that a PCP can successfully initiate the start-up of a SAGD well pair even at relatively low bottom hole temperature, what is a challenge for ESP due to high viscosity. Contrary to other SAGD projects, Joslyn wells are directly converted to pumping after the steam circulation phase. Generally, the other SAGD projects start with Gas Lift for several years before conversion to downhole pumping. Initially using ESPs, it was then necessary to perform live well interventions and it was critical to keep the wells hot enough during pump installation phase to avoid the detrimental impact of high viscosity on pump performance.

Figure 12 shows a typical ESP efficiency profile, with the strong impact of viscosity. At 250 cpo, overall efficiency of an ESP may be divided by 4 to 5 (here from 65% to 15%) and its best efficiency flowrate (@B.E.P.) reduced to 50% of the designed value for 1 cpo water. Even with lower fluid viscosity, e.g. 50 cpo, efficiency still drops from 65% to 35% (almost divided by 2) and the best efficiency flowrate and its best efficiency may be reduced to 50% of the value designed for 1 cpo.

Now, in the case of Joslyn, bitumen viscosity is about 250 cpo at 85°C, 50 cpo at 125°C and still about 15 cpo, at 160°C, when water viscosity has dropped below 0.5 cpo. That's why, even in steady hot production, the pumped fluid is necessarily still viscous and also susceptible to very viscous emulsion. Moreover sometime, a cold portion of crude entering the pump may be flowing down temporarily from the annulus, where the dynamic fluid level is going back to equilibrium. Therefore, it is not surprising that ESP did not allow to reach the best productivity from Joslyn producing wells. But the problem could be worse when we consider transient condition actually encountered by SAGD producing wells, such as well re-start, downgraded or ending production. In these circumstances, the pump intake probably has to swallow sometime a mixture of viscous slugs and perhaps even plugs of bitumen bathing in hot water medium. Then, besides drastically lowering performance of ESP vanes and disturbing the flow inside, such slugs may damage the pump,
induce vibrations, and even shocks or hydraulic hammers reflected on pump shaft, which could destroy its axial thrust.

With PCPs, keeping the well at hot temperature is not so critical. It can cool down without compromising the start-up. On Joslyn, the conversion to PCP allowed removing the need for live well interventions, saving time and reducing risks.

Moreover, PCPs are very easy to control and flowrate can be set by adjusting only the rod speed at the VFD. This allows for a very precise control of the well behavior and makes well performance optimization possible. Pump Sub-Cool and Reservoir Sub-Cool can be optimized with great accuracy so that bitumen production is maximized. Metal PCPs at Joslyn have demonstrated a very good performance with low pump intake sub-cool. However, the volumetric efficiency of the Metal PCP is a challenge. Indeed, it was confirmed that this efficiency could be significantly affected by the head applied to the pump, due to positive clearance necessary in this technology and its increase with wear. The PCP in well#A showed an overall gradual efficiency decrease with time consistent with normal wear. The PCP in well#B however showed a very high initial efficiency, but it dropped suddenly after 2 months and is now stable.

Nevertheless, it is important to mention that the production rate of these two first metal PCP wells on Joslyn exceeded that obtained from the ESP wells. Following, these promising results, a total of nine metal PCPs have been installed in the field, four of them in replacement of existing ESP installations. Production rate of the metal PCPs on the average are about 60% higher than the ESP’s run in the same well with a more continuous/smooth production performance. This shows that although ESPs by design have higher rate capacity, PCP is a preferred option for LP-SAGD well condition. Figure 13 shows production profile for well #B with ESP and after conversion to PCP. Enough field data is yet to be collected regarding realistic run life, however based on Joslyn experience, run life is presently about 10 months.

Remaining concerns and way forward

Out of the 20 metal PCP installed so far, three premature failures have been recorded. The failure analysis indicated rotor wear and stator cracking under localised fatigue induced mainly by an unbalanced movement of the rod string. Corrective actions are being implemented to prevent this phenomenon.

Conclusion

The field trials show the metal PCP as a promising artificial lift technology for hot production. Presently more than about 15 metal PCPs’ are running in Canada for SAGD and CSS operations. Further development work is being done to improve the overall metal PCP performance/service delivery in the areas of Pump efficiency and Solids handling capability and run life.

In summary, the metal PCP provides solution to several important challenges of hot pumping technology, which include:

- High temperature service (pump is rated to 350°C)
- Low intake pressure (a key challenge of LP-SAGD and eventually blow down phase of even high pressure SAGD)
- No emulsion formation (a challenge for ESP)
- Robustness and Low sensitivity to high changing viscosity (a challenge for ESP and beam pumps)
- Low power requirement

Furthermore, the unique design of the pump with a sacrificial rotor means that pump workover for rotor change-out can be performed rigless. This is an important advantage over competing high temperature ESP technology.

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Nomenclature

- P: pressure ; \( \Delta P \) or Delta-P: differential pressure
- T: torque ; Q: pump flow rate
- N or rpm: pump rotational velocity
- BEP: Best Efficiency Point (or Performance)
- CERT: Center for Engineering Research and Technology
- CETIM: Centre Technique des Industries Mécaniques
- CSS: Cyclic Steam Stimulation
- ESP: Electrical Submersible Pump
- MD: Measured Depth
- PCP: Progressing Cavity Pump
- RD: Rod Driven
- NPSH: Net Positive Suction Head
- LP-SAGD: Low Pressure Steam Assisted Gravity Drainage

References

Development status of a Metal Progressing Cavity Pump for heavy oil and hot production wells (JL.Beauquin, C.Boireau, TOTAL; L.Lemay, L.Scince, PCM), a SPE 97796 paper presented at the 2005 SPE International Thermal Operations and Heavy Oil Symposium held in Calgary, Alberta, Canada, 1–3 November 2005

SI Metric Conversion Factors

- 1 inch ( in ) = 2.54 cm
- 1 foot ( ft ) = 0.305 m
- 1 barrel (B) = 0.159 m³
- 1 bar = 10⁵ Pa
- 1 psi = 6.89 kPa
- Temperatures: \( \frac{5}{9}(°F-32) = °C \)

Figure 1: PCP principle
Figure 2: Conventional (elastomer) PCP section

Figure 3: Metal PCP principle

Figure 4: Typical Rod Driven-PCP equipment

Figure 5: One Joslyn Well Pad with Metal PCP wellheads

Figure 6: Detail of Metal PCP Drive Head used on Joslyn Pads

Figure 7: Crude viscosity versus temperature
Figure 8: 400 MET1000 Bench Test–Liquid Flowrate@ 200°C (390°F)

Figure 9: 400 MET1000 Bench Test -Vol. efficiency @ 150°C (300°F)

Figure 10: 400 MET1000 Bench Test -Vol. efficiency @ 92°C (200°F)

Figure 11: 400 MET1000 Bench Test -Overall Efficiency

Figure 12: Typical ESP efficiency affected by viscosity

Figure 13: Production increment due to conversion ESP to PCP