Expanding Production Boundaries with Electric Submersible Progressing Cavity Pumps using Enhanced Bonding and Hydraulic Regulation

Paul Skoczylas and Cyriac Job, PCM

Abstract

A progressing cavity pump (PCP) consists of a helical rotor inside a stator, creating a series of sealed cavities. When the rotor is turned, the cavities progress, transporting fluid from the inlet to the outlet. The progressing cavity design allows for a smooth, consistent flow of fluid, and is suitable for handling viscous and abrasive fluids.

In an Electric Submersible PCP (ESPCP) system, the entire pump assembly, including the motor, is submerged in the fluid being pumped.

A 16-pole permanent magnet motor (PMM) has been developed to drive the ESPCP system. This motor can provide high torque over the full range of speeds required by PCPs in artificial lift, without requiring a very low power frequency. This allows the use of existing variable frequency drives (VFD) in scalar mode and allows the signal from downhole gauges to be transmitted using the ESPCP cable.

Due to the progressing cavity design, these pumps can handle fluids with varying viscosities and maintain a steady flow and a high overall efficiency. These systems can pump a wide range of fluids, including those with high solids content, including abrasive material, high viscosity, high gas volume fraction and these can be installed in deviated or horizontal wells. The submersible design avoids the need for a rod seal at surface. Issues related to tubing wear, rod breakage and high back pressure are overcome by eliminating the rod string in the tubing.

A patented PCP stator shape has been developed to provide enhanced bonding of the stator elastomer. The pump has specially engineered rotor profiles to improve performance in high temperature applications. When used with the 198 hydrogenated nitrile butadiene rubber (HNBR) elastomer, these pumps offer an increase in the

operating temperature range in elastomeric PCPs to 150°C, while retaining all the other benefits of a PCP. The 198 HNBR elastomer also offers improved resistance to carbon dioxide (CO_2) and hydrogen sulfide (H_2S).

Standard PCPs can pump fluids with the gas volume fraction (GVF) at the intake from 30-50%. The patented Hydraulically Regulated PCP (HRPCP), however, can handle up to 90% GVF. This technology can also be incorporated into the enhanced bonding pumps.

ESPCP systems can be used with the enhanced bonding pumps and/or with the HRPCP to create a versatile Artificial Lift Solution for deviated, higher temperature, corrosive, solids laden, high gas producing oil wells and other wells deemed as problematic wells since no other form of Artificial Lift can efficiently produce these wells. This solution would be an excellent replacement for ESP systems that are typically used in such applications that operate with poor reliability and efficiency.

This new range of pumping systems offer solutions to produce wells with high deviation / dogleg severity (DLS), that have high bottomhole temperature, high GVF in the produced fluid, high solids content, while also providing increased resistance to CO_2 and H_2S gases.

Introduction

The PCP has been used in artificial lift applications for decades and has proven to be the most effective form of artificial lift in applications where the produced fluid is viscous or laden with solids. It has high overall efficiency and does not gas-lock when producing fluids with a high GVF. Traditionally, a PCP was (and most often still is) driven through a rod string from the surface. In some applications, this rod string is responsible for failures of the PCP system—either due to holes in the tubing due to rod/tubing wear, or through failures of the rod string itself. This is particularly common in wells with high dogleg severity. Other problems with PCP systems include the elastomer's inability to withstand high temperatures, and the possibility of reduced run-life when operating continuously with high gas volume fractions. Finally, in some applications a rod string is not permitted due to the inability to use a subsurface safety valve (SSSV). By combining the PCP with the drive system of an electric submersible pump (ESP), the advantages of a PCP can be obtained, eliminating the disadvantages of a rod string and surface stuffing box.

Background

While PCPs were used in artificial lift as early as the 1960s, it was in the 1980s when they started to become a widespread system for producing heavy oil from wells. Through the 1980s and 1990s, the technology developed considerably, and many variants of the system were attempted. This included the use of ESPCPs as early as the 1990s. At the time, the motors that were used were 2-pole induction motors which typically run at 2900-3500 rpm at 50-60 Hz. Some companies experimented with winding 4-pole stators to get a lower speed (1450-1750 rpm at 50-60 Hz). These high speeds required the use of a gearbox (speed reducer) to achieve the speeds that PCPs normally run at (100-400 rpm). These gearboxes developed a reputation for being a source of additional cost and failures, and there remains a reluctance to use gearboxes in ESPCP systems. It should be noted that gearboxes available today for low torque applications (<600 N·m) are significantly improved over those of thirty years ago, but the reluctance to run them remains strong.

More recently, PMMs have been increasing in popularity in the oil and gas industry. In ESP systems the main advantage of a PMM is the improved efficiency (reduced power use). For ESPCP systems, however, the PMM has the additional benefit of being able to operate at low speed, while maintaining high torque. This allows the use of PM Motors in ESPCP systems without requiring a gearbox. An ESPCP system is illustrated in Figure 1.

Figure 1. An ESPCP system

A unique ESPCP solution is offered with a 16 pole PMM which can drive a full range of PCPs. This higher number of poles allows operation at a lower speed, while maintaining a reasonable frequency (225-450 rpm at 30-60 Hz). This allows the same surface equipment to be used as in ESP systems, with minimal modification. The range of submersible PM motors are medium voltage rated with low operating current that may allow for the use of #6 AWG power cable, reducing the overall capital cost. With 4, 6, 8, or 10 pole motors, that require much lower operating electrical frequency to attain the same speeds, the transformer needs to be upsized, the downhole gauges may not be able to superimpose their data on the power cable, and the VFD may need to be specialized to run the PMM. The 16 pole motor also has higher torque density than lower pole motors, allowing a shorter motor to be used, and has reduced cogging torque, which in turn reduces vibrations.

In addition, PCP technologies have been developed and patented to improve the ability of a PCP to have extended run-life in challenging conditions. These include the HRPCP, and the newer enhanced bonding PCP.

When a PCP has free gas at the intake, it does not gas lock, unlike both ESPs and sucker rod pumps (SRP). The gas will be captured in the pump's cavities and progressed to the pump discharge, where it is released into the tubing. However, when PCPs produce a large volume of gas for an extended time, the run-life is decreased. When a PCP produces only liquid, the pressure distribution inside it can be linear—each cavity produces the same amount of pressure. Research has shown that when there is free gas at the pump intake, however, the pressure distribution is non-linear—the cavities near the pump discharge generate the majority of the pressure, while those closer to the intake produce much less. The high pressure gradient at the pump discharge generates high stress in the elastomer, which leads to an increase in hysteretic heating inside the elastomer. The high stress and elevated temperature combine to result in a lower run-life. Non-linear pressure distributions can also exist in a PCP with no gas, if the rotor fit is tight, the fluid is viscous, or the speed is high, as shown by Noble and Dunn (2011). Typical pressure distributions inside a standard PCP with different gas fractions are illustrated in Figure 2.

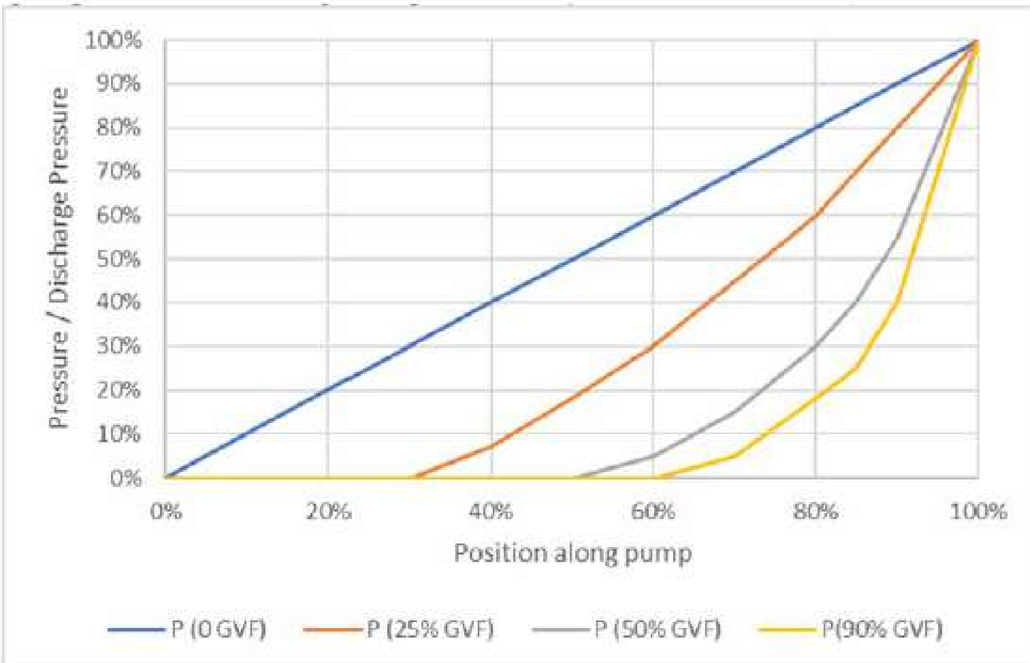

Figure 2. Pressure distribution in a standard PCP

To improve the run-life of a PCP in high gas conditions, the HRPCP was developed and patented. This pump introduces hydraulic regulators (illustrated in Figure 3) at carefully engineered points along the length of the rotor. These hydraulic regulators spread the pressure distribution more evenly along the length of the pump. This reduces the maximum stress in the elastomer, reduces the hysteretic heating, and improves the run-life of the PCP in high gas environments. While a standard PCP can tolerate a gas volume fraction (GVF) at the pump intake of up to 30-50%, the HRPCP can tolerate a GVF at the pump intake of up to 80-90%, without a reduction in run-life or reliability. The HRPCP retains all the advantages of a PCP (production of viscous oil and solids, high efficiency, no gas locking, etc.) and has no additional disadvantages.

Figure 3. A hydraulic regulator

A traditional elastomeric PCP stator is constructed by inserting a core or mould into a steel tube, and then injecting elastomer into the space between the core and the tube. This is then "cured" in an oven, after which the core is removed. Elastomer does not naturally adhere to the steel tube, however, so a special process is required to generate a bond. A glue is normally applied to the inside surface of the tube before the elastomer is injected. If the glue's bond fails, the pump will fail. PCP users have found that the bond tends to become a frequent source of failures at elevated temperatures. The exact mechanism of failure is poorly understood, but one possibility is that water molecules can diffuse through the rubber at high temperatures and cause corrosion at the surface of the steel tube, breaking the bond between the elastomer and the tube. Various methods of mechanical anchoring of the elastomer in the tube have been attempted, but it can be difficult and expensive to apply these methods inside a long, narrow steel tube. A method was developed in which a pipe of circular cross section is deformed from the outside, leaving a non-circular cross section on the inside of the tube. This process leaves two spiral grooves in opposite directions, creating a series of X shapes along the full length and diameter of the stator. These X-shapes in the stator help to prevent both axial and rotational movement of the elastomer within the stator. This mechanical anchoring not only reduces the stress on the adhesive bond, thereby making it more durable and long lasting, but also provides anchoring of the elastomer in the event that the adhesive fails. This enhanced bonding PCP has been successfully undergone a field trial in Oman. The stator of an enhanced bonding PCP is illustrated in Figure 4.

Figure 4. An enhanced bonding PCP

In order to have a pump which can operate at elevated temperatures, a specialized elastomer is required. Many PCP elastomers have a temperature limit of 80-100°C, with a few rated to 120°C or a bit higher. The 198 HNBR elastomer, which has a temperature rating of 150°C, was developed. HNBR is similar to the nitrile butadiene rubber (NBR) used in most PCPs; the difference is a hydrogenation process which replaces the double bond in the butadiene monomer with a more stable single bond. In addition, this elastomer offers superior resistance to blistering (often called explosive decompression) in the presence of CO_2 and is also more resistant to H_2S than other PCP elastomers. When used in conjunction with the enhanced bonding technology, the 198 HNBR has proven to be successful in elevated temperatures. While it is rated for operation at 150°C, it was used in a thermal well which reached a temperature of 160°C before the customer noticed the high temperature and shut the pump off. When the well later cooled to a more reasonable temperature, the pump was successfully restarted and resumed production.

When a PCP operates at an elevated temperature, there is thermal expansion of the elastomer. This expansion is an order of magnitude higher than the thermal expansion of the steel stator tube. This forces the elastomer to expand into the stator cavity. In turn, this affects the fit of the rotor inside the stator. To deal with this, rotors were engineered for use in the enhanced bonding PCP to give better performance at elevated temperatures. This reduces the torque requirements, while allowing for high efficiency at the same time as reducing the stress in the elastomer. The result is a pump with excellent performance and good reliability.

Methods

Several technologies have been discussed above, including the standard PCP and the ESP—parts of these two technologies are combined to make the ESPCP. In addition, there is the HRPCP, the enhanced bonding PCP, and the 198 HNBR elastomer. These technologies can be combined in various ways, to best meet the requirements of any given application. For example, an ESPCP can be used with the enhanced bonding PCP, or with the HRPCP, or with both.

Applications for selecting an ESPCP system with the above mentioned technology include any application appropriate for a PCP:

- Viscous fluid — including the possibility of large changes in viscosity during operation
- Produced solids — up to 30%
- Low pump submergence — 10 vertical metres with a downhole gauge, 30 m without a gauge
- Possibility of gas interference — up to 90% GVF at the pump intake
- Appropriate combination of flow rate and depth — the maximum rate depends on the depth, but it ranges from up to 1000 m^3/d from depths under 600 m, to 40 m^3/d from 2500 m
- Need to have low shear (e.g. to prevent emulsification of fluids or scale formation)
- Desire for a high efficiency system that saves power, and is a low-cost system

An ESPCP is recommended instead of a rod-driven PCP system in the following cases:

- Problems with tubing failures due to rod/tubing wear (normally in highly deviated wells)
- Problems with rod failures due to fatigue (also normally in highly deviated wells) or corrosion.
- A desire to have no rotating seal or stuffing box at surface — for example in ecologically sensitive areas
- High frictional pressure losses due to lower flow area in the tubing because of the presence of a rod string
- A need to have a SSSV in the completion
- A requirement for multiple well control barriers during installation and operation such as in offshore applications, or due to company polices — an ESPCP can be installed anywhere an ESP can

Note that in applications where the speed of a rod-driven PCP is reduced to maximize the run-life of the system by reducing rod fatigue failures and holes in tubing due to rod wear, the use of an ESPCP system allows for increased production as there is no longer a need to limit the speed.

Once an ESPCP has been selected as being the appropriate solution for a well a choice is to be made regarding the components of the system. In most cases, a 16-pole PMM is chosen to drive the system. This allows the electrical frequency to remain within a range that permits the same transformer and downhole gauges to be used as in a comparable ESP system. At the low frequencies that a motor with fewer poles would require, the transformer would have to be oversized, and the gauges would not be able to superimpose their signal on the power cable. This would then require the choice of running without a downhole gauge, or running a separate cable for the gauge signal, at an increased cost and completion complexity. The alternative would be to run a lower pole / higher speed motor with a gearbox in the system. While modern gearboxes are more reliable than those used in early ESPCP systems, it is still an additional point of failure. Normally, an ESPCP system would only include a gearbox where necessary. The primary example would be highly deviated (high DLS) wells. The use of a gear reducer allows for a significantly shorter system, which can be run through wells with higher DLS.

At the time this article is being written, the torque limits for the 16-pole PMM is 1000 N·m for systems which can be installed in 5.5" casing, and 2000 N·m for systems that can be installed in 7" or larger casing. For slim hole systems (4-1/2" casing), a 4 pole PMM is available, allowing operation at 250 to 500 rpm, with up to 400 N·m of torque.

The choice of seal system is made in the same way as it would be for an ESP, based on factors such as well depth and the hole angle.

Because a PCP has eccentric rotation, a flex-shaft assembly is installed between the pump and the motor seal; this shaft travels through the intake section of the ESPCP system. The shaft allows the PCP rotor to orbit eccentrically, while the motor seal shaft rotates concentrically, as it would with an ESP. A bearing sub is installed with the ESPCP system, between the flex-shaft and the motor seal, in order to ensure that the motor seal's bearings are not affected by the additional radial loads from the flex-shaft. The total axial load from the PCP is estimated (based on the pump geometry and the intake and discharge pressures), and this is used to determine if the motor seal's thrust bearing is adequate. The motor seal section is generally an ESP seal, which may not be adequate for the thrust load generated by a PCP. If the calculation determines that additional bearing capacity is required, an additional thrust bearing sub is included. The shafts are shimmed in such a way as to ensure that the thrust bearing sub takes the axial load rather than the motor seal section's bearing.

When an ESPCP system is being selected, the use of an HRPCP is strongly recommended. This technology is proven to demonstrate improved run-life when there may be high gas at the pump intake but has no downside in the event of there being no gas. It retains all the advantages of a standard PCP, with the additional advantage of being able to tolerate up to 80-90% free gas volume at the pump intake. The small additional cost of the HRPCP technology is considered cheap insurance in the event that there is gas production, even when minimal gas is expected.

The HRPCP technology is modified slightly for an ESPCP as compared to a rod-driven PCP. This is because the hydraulic regulators are not uniformly spaced through the pump. They are located with a greater concentration near the discharge end of the pump, as that is where the pressure gradient would be higher if there were no hydraulic regulators. With a rod-driven PCP, the rotor head is located at the discharge end of the pump, while an ESPCP's rotor head is at the pump intake. Therefore, the positions of the hydraulic regulators must be inverted.

The location of the rotor head poses another issue, whether a standard PCP or HRPCP is used. As the rotor is driven from the bottom, it must be rotated in a counter-clockwise direction (looking from the motor towards the pump). This is opposite to the direction that a rod driven pump is turned. Therefore, the standard right-hand threads that are normally used in a PCP rotor's head cannot be used in an ESPCP, or the rotor would unscrew from the drive under torque. There are various possible solutions, including welding the rotor to the flex-shaft, drilling a hole and inserting a pin, using left-hand threads, or using splines instead of a threaded connection.

While this paper has highlighted the 198 HNBR elastomer for use in elevated temperatures, or with higher CO2 or H2S contents, many wells do not have these challenges. The 159 NBR has proven itself to be highly reliable in a wide range of conditions, including the possible presence of some CO2 or H2S. It is the first choice for most applications in oil and gas wells. If there is a higher solids content in the produced fluid, a softer elastomer such as the 205 NBR elastomer has been shown to be very effective. If there is high aromatics (but minimal solids, and a temperature under 80°C), then the 204 FKM (fluorocarbon) elastomer is selected. However, when the temperatures are high (up to 150°C), or the CO2 or H2S levels are high, then the 198 HNBR, would be the first choice of elastomer.

The enhanced bonding PCP, in conjunction with the 198 HNBR elastomer, allows the operation of an elastomeric PCP at temperatures up to 150°C. This technology is proven and is also 100% compatible with both ESPCP technology and the HRPCP technology.

Results

The existing rod driven PCP technologies (HRPCP and enhanced bonding PCP) have extensive field experience with excellent results. ESPCPs have also been used in the field since at least the 1990s. The PMM solutions are newer, but still have several years of good success. The 16 pole PMM is even newer still, but has been successfully tested in the lab with a VFD in scalar mode (and 1000 m of ESP cable), and several systems have been installed in oil and gas wells worldwide. The author's company has installed ESPCP systems (with two or four pole motors) in Kuwait, Australia, and Oman, as well as supplied several hundred PCPs for use in ESPCP systems assembled by third parties in countries such as China. A system installed in Kuwait is describe further below.

Some publications describing the field experience of each of these technologies are summarized below.

HRPCP

The most complete and recently published summary of the HRPCP was by Skoczylas (2022). This paper contains an extensive list of references to literature that describes the development and initial field trials of the HRCP technology. It also contains an analysis of three recent field applications of the technology. In addition, Skoczylas and Brodbin (2023) presented a webinar that further updated the case study for the HRPCP in Canada.

A paper by Sharan (2024) describes the successful use of an HRPCP (described in the paper as a "gas handler PCP") in a coalbed methane field.

An early use of the PMM ESPCP, combined with the HRPCP was described by Al Ajeel et al (2016). In this study, not only was the run-life of the combined system longer than the run lives of the previous rod driven PCPs in the same well, but the power usage was decreased by almost 70%. While the paper was published after 17 months of running, the system ran without replacement for the complete three-year period of the contract.

ESPCP

There are numerous publications in the literature related to the ESPCP. There are reports that it was tried in Canada as early as 1966 (Matthews et al, 2006). It is clear that Husky Oil (a Canadian company at the time) filed a patent on the technology in 1971 (Corkill, 1971). The authors are unable to pinpoint the earliest publications on this topic, but are aware that there were multiple presentations at the 1998 SPE ESP workshop on the topic—papers from this workshop are not, unfortunately, available through OnePetro. One paper by Skoczylas and

Alhanati (1998) does not specifically refer to the ESPCP, but was written to address the issues of cooling an ESP motor when viscous oil was being pumped, as would be the case in an ESPCP.

Chacula and Liu (2000) presented on a very early use of PMM systems to drive ESPCP systems.

At the 2001 SPE PCP workshop, there were three different presentations on the use of ESPCP systems: Dunlap (2001), Saveth (2001), Zabel (2001).

Some later publications on the successful applications of ESPCP systems include Tello Bahamon et al (2017), Franks and Cochran (2014), among many others.

Enhanced Bonding PCP

This is the newest of the technologies described here, and there is only a single publication available, by Al Jabri et al (2024), who describe the successful field trial conducted in Oman, with over 40 installations at the time the paper was written (December 2023). This number has significantly increased since then.

Conclusion

The ESPCP is an artificial lift system which provides all the advantages of a PCP, without the disadvantages associated with the rod string and the surface stuffing box. The use of a PMM in the ESPCP, instead of the traditional induction motor used in most ESP systems, allows for high torque at the low speeds used by PCPs. The 16 pole PMM used in the ESPCP allows the low speeds without excessively low electrical frequencies, which in turn allows a broader range of existing oilfield VFDs to drive the ESPCP, while also allowing the gauge signal to be carried on the electrical cable. Furthermore, when low frequencies are avoided, there is no need to oversize the transformer.

While the simplest version of the ESPCP addresses the disadvantages of the PCP's rod string, other technologies, which are compatible with the ESPCP can be added to remove other disadvantages. The HRPCP allows a PCP to have a long run-life in the presence of gas. The enhanced bonding PCP provides for an improved bond, greatly reducing failures associated with elastomer debonding. When used in conjunction with the 198 HNBR elastomer, the temperature limit is as high as 150°C. The 198 HNBR also has improved resistance to CO_2 and H_2S.

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