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Progressing Cavity (PC) Pump Design Optimization for Abrasive Applications

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Abstract

The progressing cavity (PC) pump is well established as the pump of choice for handling abrasive solids. PC pump design can be optimized to achieve the best wear performance available for a given size. The wear optimization of the PC pumps is achieved through geometric design for minimum internal fluid velocities and by selecting proper materials of construction.

Wear causes PC pump failure by gradually reducing the volumetric efficiency and increasing pump slippage. This paper focuses on the parameters that influence pump wear, describes wear mechanisms, reviews design techniques for wear optimization , and presents field data to support some of the claims.

Background

Pump Design Parameters. Figure 1. shows the cross section of a progressing cavity pump.

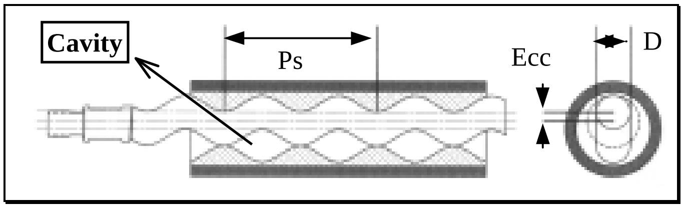

Figure 1.

Definitions:

$P_s \approx$ Stator Pitch
$D \approx$ Rotor/Stator Minor Diameter
$Ecc \approx$ Rotor Eccentricity

A progressing cavity pump consists of a helical steel rotor which turns within a stationary tube with a helical elastomeric lining (stator).

As the rotor turns inside the stator, fluid moves through the pump from cavity to cavity. As one cavity diminishes, the opposing cavity increases at exactly the same rate which results in a pulsationless positive displacement flow through the pump. The cavities are separated from each other by a series of seal lines which are created between the rotor and stator. The pressure capability of a pump is a function of the number of times the progressing seal lines are repeated. PC pump manufacturers rate the pressure capability of a pump as a function of the number of pump stages. Although somewhat arbitrary, each stage is between one to one and a half of a stator pitch length and is capable of handling 100 psi differential. If cavity pressure increases beyond the seal limits, the seal lines will open, and fluid will “slip” from one cavity to the other at a very high speed. The PC pump slippage is generally a function of pressure differential across the pump and it changes depending on the compression fit of the rotor and stator.

Flow Rate. Pump flow rate is a function of design parameters such as stator pitch (P_s), rotor diameter (D), and pump eccentricity (Ecc). Equation 1. defines this function:

$$\mathbf{Q = K*P_S*4*Ecc*D*N}$$

where:
$Q \cong$ flow rate
$N \cong$ number of revolutions per unit time
$K \cong$ conversion factor

Equation 1.

Fluid Velocity. Nominally, for each rotation of the rotor, fluid will move one pitch length of the stator. Therefore, fluid nominal velocity in the axial direction of the pump is defined by Equation 2:

$$\mathbf{V_{fluid}= C*P_s * N}$$

Where:
$V_{fluid} \cong$ nominal fluid velocity
$N \cong$ number of revolutions per unit time
$C \cong$ conversion factor

Equation 2.

Equation 2. Assumes that the fluid particles travel along a straight line. In reality, fluid does not travel in a straight line and calculation of the maximum velocity must consider the longest fluid path along a *circular helix* defined by the stator pitch and diameter. The theoretical maximum velocity within a PC pump is therefore defined by Equation 3.

$$\mathbf{V_{MAX} = C * N * (P_s^2 + \prod^2 (D + 4Ecc)^2)^{1/2}}$$

where:
V_{MAX} ≅ theoretical maximum velocity
C ≅ conversion factor

Equation 3.

Wear Phenomenon

Abrasive wear of PC pumps is one of the most common modes of failure in down-hole applications. High speed particles (sand) traveling through pump cavities abrade both rotor and stator. This causes the seal lines between the rotor and stator to become less effective and results in higher pump slippage. The increase in the pump slippage will reduce pump volumetric efficiency and will gradually destroy the pump.

There are many factors that contribute to rotor and stator wear. Among the most important are particle size, concentration and hardness, pump rotational speed and number of stages, and velocity of the solids traveling through the pump.

Particle Size. There is little or no uniformity in the size of sand grains that find their way into the pump. Coarser grains (less than 20 mesh) can do more damage to the PC pumps compared to finer powder-like sands (higher than 100 mesh .) However, high concentration of very fine powder-like sand can also abrade rotors and stators. Larger sand particles can not easily pass through the pump seal lines. These particles are often partially embedded in the inner surface of the stator (Figure 2.) and continually rub against the rotor during pump operation.

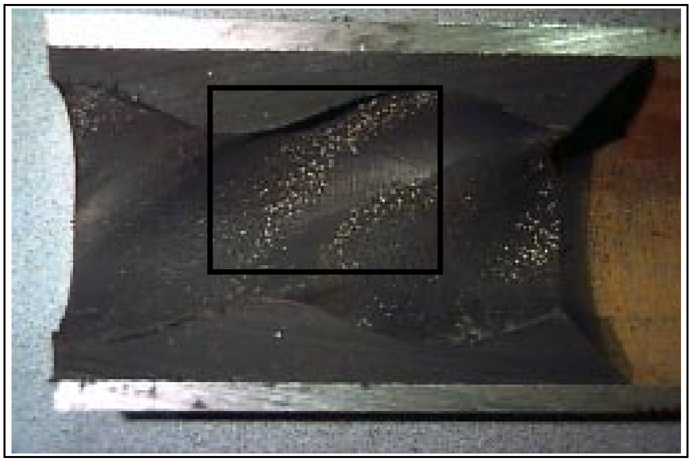

Figure 2. Particles embedded on the stator surface

The rubbing of the rotor against the sand particles combined with the high speed impact of hard particles with the rotor contribute to the formation of wear patterns similar to Figure 3.

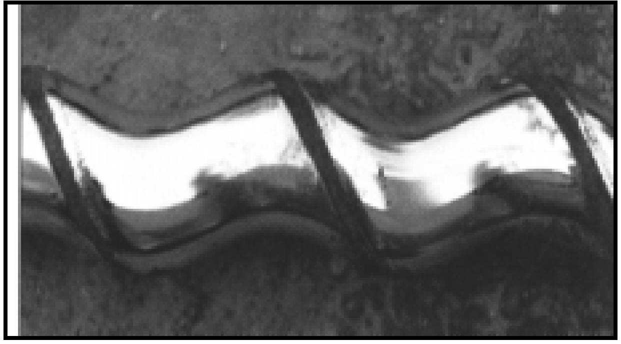

Figure 3. Deep grooves on the rotor crest resulting from extreme abrasive conditions

Pump Rotational Speed and Number of Stages. Equations 1., 2. and 3. show that PC pump internal velocity and flow rate increase as pump speed increases. As these parameters increase, the rate of particle impact to the rotor and stator increases which will accelerate rotor and stator wear. In general, the more abrasive the fluid, the slower the pump must operate. The amount of wear in an abrasive application is closely proportional to the speed squared of the pump. One detrimental effect that speed reduction may have on pump life may best be shown by the performance curves of Figure 4 for a speed A and B where B is one half of A.

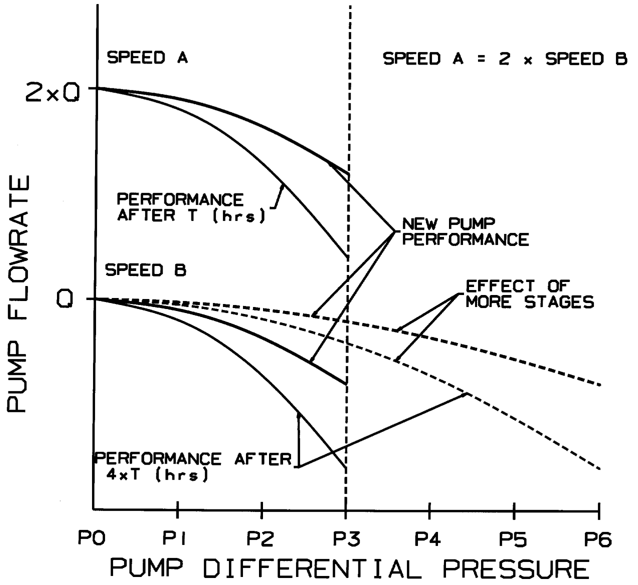

Figure 4. Effect of wear on progressing cavity pump performance

Since wear is assumed proportional to speed squared, it would take four times as long for a pump to wear at speed B compared to the same pump running at speed A. Although it would take almost four times as long to reach the same amount of wear at half the speed, the reduction in the volumetric efficiency[1] would be doubled. In most applications, this effect will negate the usefulness of the longer life expected by speed reduction. To compensate for this effect, using more pump stages for an abrasive application is recommended. This helps maintain high volumetric efficiencies under pressure at even the lower speeds, reducing the effect of wear on flow rate and thereby increasing the time between pump replacement. Therefore, abrasive wear of PC pumps can be improved by decreasing pump rotational speed and by increasing the number of pump stages.

Sand Concentration. Most wells produce some amount of sand for varying periods of time which reduces rotor and stator life of a PC pump. Sand cuts of 10 to 30 percent by volume are considered to be heavy sand concentrations. In general, wear is directly proportional to the number of particles that come in contact with the rotor and stator. Therefore, in the absence of other failure mechanisms and for otherwise identical operating conditions, change in wear life is proportional to the change in sand concentration.

Particle Hardness. The degree of particle hardness also affects rotor and stator wear. If sand grains are harder than the surface of the rotor, shear on the rotor surface will cause abrasion. Generally, rotor wear is accelerated as the particle hardness increases. Some times, the affect of rotor wear is accelerated when corrosion induced rotor surface cracks are also present. For example, in sour wells, the effects of hard iron-sulfide particles are accelerated due to rotor surface corrosion cracks induced by the presence of H_2S.

Particle Velocity. Velocity of the solids traveling through the pump is the most important parameter that causes rotor and stator wear. Particle speed within a PC pump can be separated into two categories: 1) predictable pump internal velocity and 2) unpredictable particle speed due to pump slippage. To reduce wear in PC pumps, pump internal velocity and slippage must be minimized. This can be accomplished through geometrical design optimization and proper selection of the pump for the application.

Pump slippage accelerates wear by causing fluid and particles to travel at higher speed between rotor and stator seal lines. Compression fit between the rotor and stator can be optimized to reduce pump slippage and improve wear life. The following paragraphs describe pump design optimization, materials of construction, and pump selection techniques that can increase pump life in abrasive applications.

PC Pump Design for Abrasive Applications

Wear in PC pumps increases as a function of fluid and particle speed within the pump. The goal for PC pump design optimization is to minimize the particle internal velocity while meeting pump flow and lift requirements. Equation 1. describes flow rate as a function of pump rotor diameter (D), eccentricity (Ecc), and stator pitch (P_s). Flow rate can also be described by Equation 4.

$$\mathbf{Q = A_{cavity} * V_{fluid}}$$

Where:

$A_{cavity} \cong$ Area of the pump cavity cross section or (D*4Ecc)

$V_{fluid} \cong$ Nominal velocity of the fluid and particles inside the pump

Equation 4.

Equation 4 illustrates that pump cross sectional area (A_{cavity}) must be maximized in order to minimize fluid velocity for a desired pump flow rate. Figure 5. shows the relationship between pump design parameters and A_{cavity} . From Figure 5., the maximum possible pump cross sectional area and therefore minimum pump internal velocity is achieved when the ratio of rotor diameter to pump eccentricity (D/Ecc) is equal to 4.

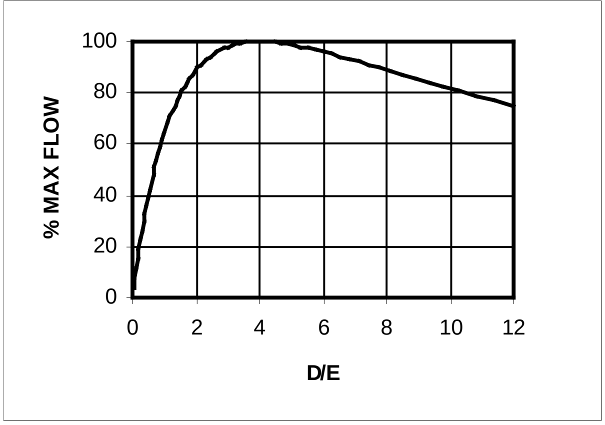

Figure 5. Relationship between pump design parameters and PC pump maximum possible flow rate

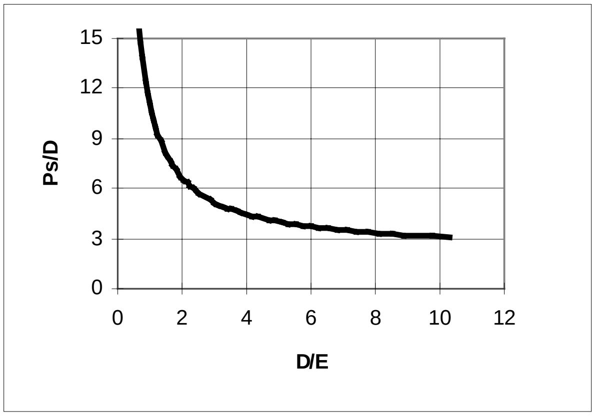

Figure 6. Stator pitch length which minimizes velocity

Figure 6. describes a more complicated relationship between the pump design parameters. This figure shows the stator pitch length (P_s) which minimizes the V_{max} (Equation 3.) and therefore provides the best wear performance for a required pump capacity.

Figure 7. further demonstrates the necessary relationship

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[1] volumetric efficiency is defined as the flow rate at the pressure divided by the flow rate at zero pressure differential.

between the stator pitch, pump eccentricity, and pump diameter to achieve lowest internal velocity.

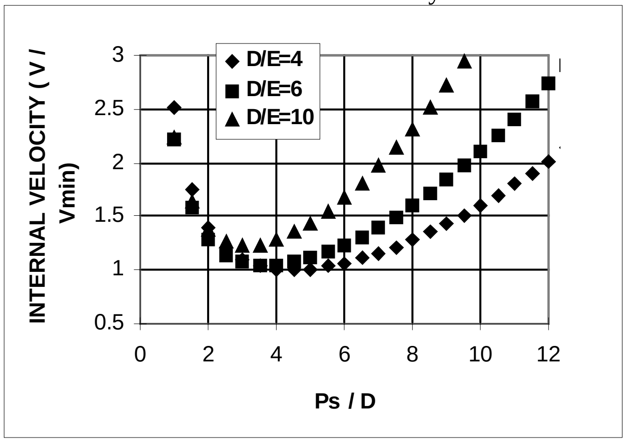

Figure 7. Relationship between pump internal velocity and design parameters

Pump design optimization is typically conducted using Figures 5 and 6 as the starting point. However, manufacturing limitations, well casing size, pump pressure and flow requirements often constrain pump geometrical parameters. For example, most PC pump rotors are designed with the D/E ratio of larger than four (4) to insure adequate rotor strength to meet torsional and bending stresses. Also, stator pitch is typically lengthened beyond the optimized value to increase the pump capacity per revolution (at the expense of higher internal velocity.) Consequently, it is not always possible to optimize a pump solely based on the wear performance, and often pump wear resistance is compromised in order to meet other design requirements.

Materials of Construction for Abrasive Applications

Rotor Coating. Rotor wear is the primary cause of pump failure in abrasive applications. To date, the majority of PC pump rotors are hard chrome plated. Hard chrome is adequate for medium to low abrasive environments. However, life of a chrome plated rotor can be reduced by as much as 50% in high flowing wells that produce more than 10% sand.

Alternative rotor coatings using thermal spray processes have been successfully used by PC pump manufacturers to improve rotor life in abrasive applications. Field trials of these rotors have shown to double or triple the life of chrome plated rotors in similar applications. The alternative coatings are typically more expensive than chrome and operators must carefully weigh the economic benefits of using these rotors for their specific applications.

Stator. Elastomeric stators give PC pumps an advantage over other down-hole pumps in handling abrasive slurries. The flexibility of the elastomer allows large abrasive particles to go through the pump or to imbed rather than abrade the stator. The PC pump stator elastomer can be optimized for best wear resistance while meeting other mechanical and physical properties.

The elastomer wear resistance optimization involves creating a balance between the elastomer's cross-link density, physical strength, tear resistance, and fracture properties. As the hard particles stress the elastomer upon contact with the stator, energy is either converted to heat or stored elastically in the polymeric chains of the rubber. The elastic energy stored within the rubber becomes available as a driving force for the rubber fracture propagation. Once the fracture has occurred, tear properties of the rubber will control fracture propagation within the rubber.

The elastomer for PC pumps used in abrasive applications must be soft enough to allow the passage of large particles through the seal lines without damaging the rubber. Optimum hardness range of the elastomer for maximum life in abrasive applications is between 50 to 65 durometer (shore A.) In addition, physical and mechanical properties of the rubber must be optimized to allow hard particles to imbed inside the rubber without allowing the small surface fractures to propagate. As in design optimization, it is not always possible to select the most wear resistant elastomer for an application. For example, although the most abrasion resistant rubber compound is a high grade of natural rubber, its lack of oil resistance eliminates its use in oilfield applications. Stator elastomer selection must take into consideration other down-hole conditions such as temperature, water cut, aromatics concentration, or H_2S presence. The abrasion resistance of a stator elastomer is some times compromised to meet these down-hole conditions.

Pump Selection

Selecting a PC pump for an abrasive application involves several steps. First, the pump must be rated for the application flow requirements. The user must then select a pump which can produce the desired volume at lowest fluid internal velocity and at lowest possible pump rotational speed. The user must also consider de-rating pump pressure per stage to maximize pump life for the application. Once these criteria are considered, the materials of construction must be selected for maximum wear life.

Material selection can greatly influence the life of a PC pump. To select the right material for an application, all down-hole conditions which may contribute to rotor and stator failure must be considered. Materials for the pump must be selected to achieve the best overall performance for the application. For those applications where abrasion is the primary concern, stator material must have superior wear properties as described in the previous section. Hard chrome or other wear resistant rotor coatings must also be considered to improve rotor life in abrasive applications. Selection of the pump material may also require an economic justification since some of the alternative materials might be more expensive than others.

Field Results

New elastomers and rotor coatings for abrasive applications have been studied in many different locations in Canada and the United States. Figure 8 shows the improvement in pump life obtained using pumps optimized for abrasive applications in the sandy (3 to 20 percent by volume) Lloydminster region in Canada[2].

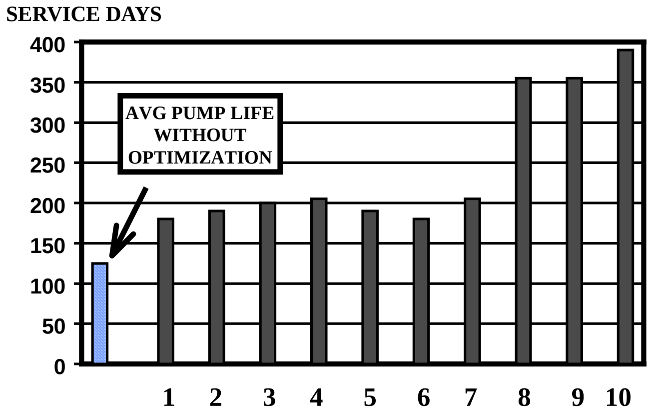

Figure 8. Improvement in average pump life of ten different wells in Lloydminster Canada using more abrasive resistant elastomer

Summary

Progressing cavity pumps can be optimized to provide longer life in abrasive applications. Wear optimization of PC pumps is achieved through pump geometric design, proper selection of stator elastomers and wear resistant rotor coatings, and proper sizing of the pump for the application. Down-hole conditions such as concentration, size, and hardness of the sand particles influence pump wear. PC pump life can be extended by reducing particle velocity through the pump, by running the pump at lower speed, and by adding more stages to the pump. Field results show that the life of PC pumps can be increased significantly if pumps are optimized for the abrasive conditions.

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[2] The data was obtained in December 1996 and all of the pumps shown in this Figure were still in operation.