PROGRESSING CAVITY PUMPS PROPER SELECTION AND APPLICATION

by

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ABSTRACT

The design and construction of progressing cavity pumps permits them to pump virtually any fluid from clean, low viscosity fluids like oil or water, to delicate products like whole cherries, to very abrasive, highly viscous fluids.

Progressing cavity pumps use a single threaded rotor rolling eccentrically in a double threaded helix with a pitch length twice that of the rotor. This combination results in a series of sealed cavities 180 degrees apart that progress from the suction end to the discharge end of the stator, as the rotor rotates. As one cavity is closing, the other is opening at exactly the same rate so the sum of the two discharges is constant. The result is pulsationless flow without the use of valves. This makes the progressing cavity concept ideal for metering applications or other applications where predictable flowrates are essential.

The primary focus herein is on the proper selection of progressing cavity pumps for different types of applications. Applications discussed include the pumping of shear sensitive fluids, the pumping of extremely abrasive fluids, the pumping of a fluid in a metering application, and the pumping of a high viscosity fluid.

INTRODUCTION

The progressing cavity principle was invented by Rene Moineau in 1929, and was first introduced into the United States in 1936. Progressing cavity pumps developed on the original Moineau concept are a unique type of positive displacement pump that are used in a variety of pumping applications. A cross sectional drawing of a typical progressing cavity pump is shown in Figure 1.

Positive displacement pumps are typically either rotary or reciprocating pumps. Included in these two classifications are external gear, internal gear, piston, diaphragm, lobe, screw, peristaltic, and progressing cavity pumps. The one common feature of all of these pumps is that they have a definite displacement associated with each stroke, revolution, or cycle of the pump. The similarity between these other pumps and progressing cavity pumps generally ends there. Of all the types of pumps available,

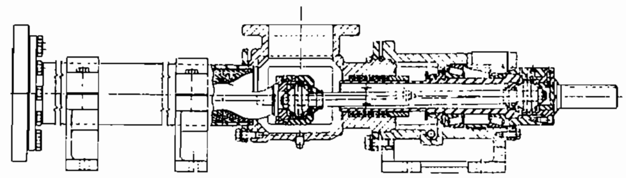

Figure 1. Cross Sectional View of a Typical Progressing Cavity Pump.

progressing cavity pumps are able to handle a wider range of fluid viscosities and properties than any other type of pump.

Unlike other types of pumps, progressing cavity pumps can pump virtually any fluid from clean, low viscosity fluids like oil or water, to delicate products like whole cherries, to very abrasive or highly viscous fluids. Although the unique design of progressing cavity pumps makes them useful for a variety of pumping applications, those application areas most commonly addressed involve shear sensitive fluids, abrasive fluids, metering applications, and viscous fluids. Each of these applications calls upon specific features of progressing cavity pumps and proper use of the pumps in these applications requires a thorough knowledge of progressing cavity pump principles. A brief review of these principles will enable the reader to appreciate the complexity of selecting the proper pumps for these applications.

DESIGN AND OPERATING PRINCIPLES

Progressing cavity pumps, in their simplest form, consist of a single threaded helical screw, or rotor, rotating eccentrically inside a double threaded helical nut, or stator. The basic design of a progressing cavity pump rotor and stator is shown in Figure 2. The pitch length of the stator is twice that of the rotor. The combination of a rotor and stator represents a set of progressing cavity pumping elements. The elements previously described are identified as 1:2 profile elements, for one lead or lobe on the rotor and two leads or lobes in the stator. More complex progressing cavity pump and motor designs are possible, such as 9:10 designs where the rotor has 9 lobes and the stator has 10 lobes. According to Moineau's original theory, any combination is possible so long as the stator has one more lobe than the rotor.

This presentation is focused on the 1:2 profile although the principles and concepts discussed will apply to other profiles and to some extent, other types of pumps.

As the rotor turns inside the stator, cavities are formed that progress from one end of the stator to the other end. In one revolution of the rotor two separate cavities are formed, one cavity opening at the same rate as the second cavity is closing. This results in a predictable, pulsationless flow. In most progressing cavity pumps, the stator is formed with an elastomeric material that fits on the rotor with an interference fit. The compression fit between the rotor and stator results in the formation of seal lines where the rotor contacts the stator. This assures separation of the individual cavities progressing through the pump with each revolution of the rotor. The use of an elastomeric stator permits progressing cavity

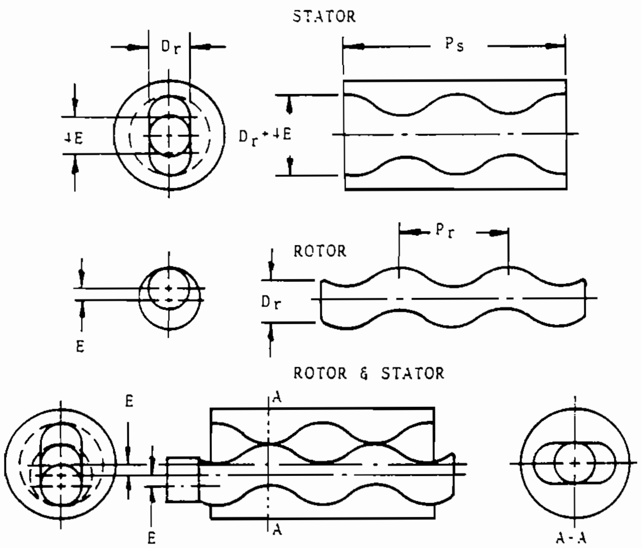

Figure 2. A Progressing Cavity Pump has a Helical Rotor with a Single Lead (or Thread) Rolling Eccentrically in a Helical Stator with Two Threads, the Pitch Length of the Stator Being Twice that of the Rotor.

pumps to pump abrasive materials and fluids with large solid particles in suspension, and also enables the pump to be self priming up to 28 ft.

Although the design of PC pumping elements appears complex, calculations of displacement, maximum particle path through the elements, internal velocity, and shear rates are quite simple. For example, the displacement of a progressing cavity pump is stated by:

$$Q = 4E_r D_r P_s, \tag{1}$$

where E_r is the eccentricity of the rotor, D_r is the rotor minor diameter, and P_s is the stator pitch length, as shown in Figure 2.

Obviously, changing any of the three design variables will result in a change in the displacement of a progressing cavity pump. There are certain ratios of eccentricity to diameter and diameter to pitch length that provide optimum displacement. Still, it is customary to deviate from these optimum values to enhance the ability to manufacture the elements and to improve other operating characteristics such as torque and abrasion resistance.

Similarly, the maximum particle path through progressing cavity pump elements is expressed by:

$$((Pi)^2 (4E_r + D_r)^2 + P_s^2)^{1/2}. \tag{2}$$

Since E_r and D_r are typically small compared to P_s, the flow of fluid through the elements is only slightly different than a straight line between the suction and discharge. This relationship enhances the ability of progressing cavity pumps to handle shear sensitive fluids with a minimum of product degradation.

The two fundamental considerations in selecting any pump are the flowrate and differential pressure required. It was previously shown that the displacement of progressing cavity pumps is a function of the rotor and stator geometry. The displacement per revolution times the operating speed will dictate pump capacity. Although fluid properties do not directly affect pump displacement, they do affect the maximum recommended pump rotational speed. Therefore, they affect the maximum capacity of a specific rotor and stator geometry. This will be discussed in more detail.

The pressure capability of a progressing cavity pump is determined by the number of "stages" a pump has. As previously indicated, the compressive fit between the rotor and elastomeric stator results in the formation of a series of seal lines. The set of seal lines formed in one stator pitch length constitutes a stage. A two stage pump has twice the pressure capability of a single stage pump, a three stage pump has three times the pressure capability of a single stage pump, etc. The physical relationship of a one and three stage rotor and stator and a comparison of pressure capability is presented in Figure 3. Theoretically, an infinite number of stages is possible, but from a practical standpoint, the number is limited by manufacturing considerations and by the torque limitations of various rotor diameters.

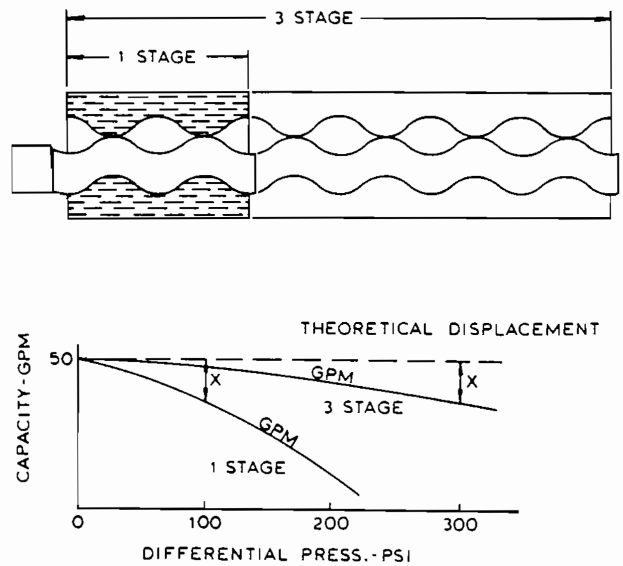

Figure 3. The Number of Stages Determines the Pressure Capability of a Progressing Cavity Pump.

Most progressing cavity pump manufacturers recommend a maximum differential pressure of 80 to 90 psi for a single stage rotor and stator pumping clean fluids. This limitation is reduced for abrasive fluids in order to ensure satisfactory pump life. This recommendation also may be reduced for certain stator elastomers, such as 35 durometer natural rubber.

Progressing cavity pump stators also can be formed from rigid materials, like tool steel or stainless steel. Obviously, pumps with rigid stators require a clearance between the rotor and stator, the result being a significant amount of internal leakage, or slip, when pumping low viscosity fluids. For this reason, pumps with rigid stators have customarily been limited to the pumping of fluids with viscosities over 2000 centipoise. Recent advances in the machining of rigid stators have permitted much closer fits between the rotor and stator permitting the successful pumping of lower viscosity fluids.

The pressure limitation of rigid stator pumps is primarily a function of the fluid viscosity. The more viscous a fluid is, the higher the pressure capability will be per stage. With high viscosity fluids it is not unusual to have pressures per stage in excess of 250 psi. Therefore, the maximum pressure capability of progressing cavity pumps with rigid stators readily exceeds that of pumps with elastomeric stators. Pumps with rigid stators are typically used for pumping relatively clean fluids, where the fluid viscosity exceeds 200 centipoise, where the fluid temperature exceeds the limitations of compatible elastomers, and where the fluid is generally not compatible with elastomeric materials. Since the selection and application of rigid stator pumps is quite involved, only progressing cavity pumps with elastomeric stators are discussed.

In the brief discussion of rigid stators the internal leakage, or slip, was mentioned. Pumps with elastomeric stators also have some slip and the proper selection of pumps requires an understanding of this characteristic of progressing cavity pumps. Slip is the difference between the capacity at zero differential pressure and some elevated pressure. At low differential pressures per stage, slip is practically negligible, as shown by Figure 4.

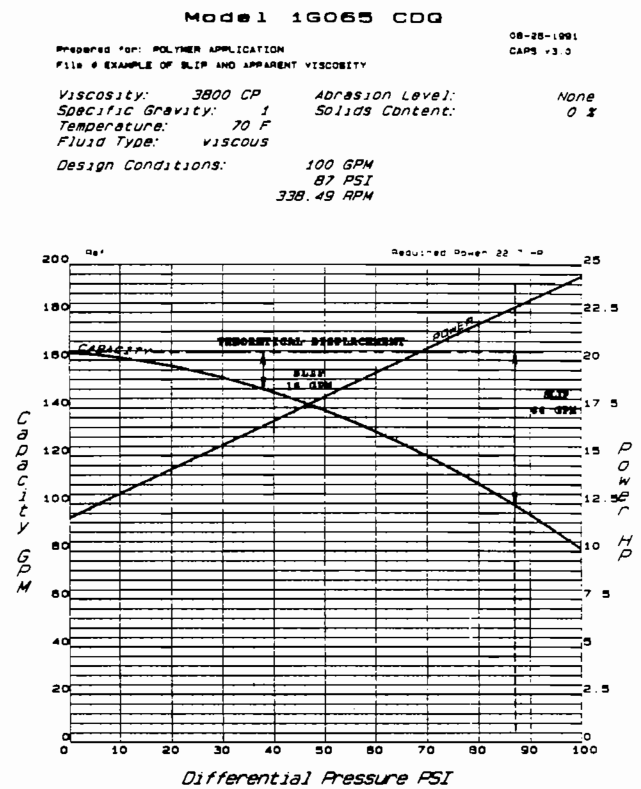

Figure 4. As the Differential Pressure Increases in a Progressing Cavity Pump, the Internal Leakage or Slip Also Increases.

However, at increasing pressures slip can be significant. In some applications, such as metering a fluid, pumping a shear sensitive fluid, or pumping an abrasive fluid, slip should be kept to a minimum. This can be accomplished by increasing the number of stages.

Slip in progressing cavity pumps is affected by fluid viscosity and temperature and by the pressure per stage. Viscosity is that property of a fluid that causes the fluid to resist flow. The higher the viscosity of a fluid, the less slip there is in a progressing cavity pump. Fluid temperature has a similar effect on slip. Since the coefficient of thermal expansion of elastomeric materials is approximately 10 times that of steel, pumping a hot fluid, or in some instances, operating a progressing cavity pump in a hot environment, will result in an increase in the compression fit between the rotor and stator. This will result in a decrease in the slip. Unfortunately, the decrease in slip will be accompanied by higher operating torques and most significantly, higher starting torques. The increased torques are not normally a problem at fluid temperatures below 150°F. However, at higher temperatures, the use of an undersize rotor is normally recommended to avoid possible problems associated with the higher starting torques.

PUMP SELECTION CONSIDERATIONS

With these basic principles and characteristics of progressive cavity pumps in hand, lets look at specific fluid conditions and important considerations when selecting a pump. First to be considered is an application involving a shear sensitive fluid. Although the shear rates in progressing cavity pumps are typically low, on the order of 100 to 200 inverse seconds throughout the years, the characteristic approach to handling shear sensitive fluids was to pick a large pump operating at a slow speed. Since the shear rate of progressing cavity pumps is a function of rotor/stator geometry and speed, the reduced speed provided a low shear rate. Unfortunately, this approach often only produces marginal results and, in some cases, is even detrimental to the fluid.

A typical performance curve and performance data for a pump for a polymer application are shown in Figure 4. Although this pump might appear to be a good choice based on pump speed and resultant shear rate (196 inverse seconds), the fluid will be subjected to a considerable amount of shearing with increasing differential pressures due to the amount of slip in the pump.This slip, or internal leakage, can be a substantial percentage of the fluid pumped. This is fluid that is not passing through the pump in the nearly straight line fashion previously discussed, but instead is being forced across the seal lines in the pump. Obviously, since there is normally a compressive fit between the rotor and stator, the amount of shearing imparted to the fluid as it displaces the elastomeric stator material and breaks the seal line is significant. When the amount of fluid being forced to do this is relatively large compared to the pump output, as in this case, the amount of shearing of the product is significant.

There are several ways to minimize the amount of shearing imparted to the fluid as a result of slip. The most obvious is, of course, to increase the number of stages in a pump, thereby reducing the amount of slip. The second, and perhaps not so obvious, is to reduce the size of the pump, thereby reducing the amount of slip when compared to the produced flow. The use of a smaller pump will increase the pump speed and internal shear rate, but usually not to a magnitude that will adversely affect the fluid. Another way to reduce slip is to increase the rotor size thereby increasing the compression between the rotor and stator.

As a rule, the slip in a progressing cavity pump should not exceed 10 to 15 percent of the produced flow when pumping extremely shear sensitive fluids. The key to properly sizing a pump for a shear sensitive fluid is to maximize the pump volumetric efficiency, while minimizing the internal velocity and corresponding shear rate.

A second type of application progressing cavity pumps are commonly used for is metering applications. When properly applied for these applications, they perform flawlessly.

The best way to ensure successful metering applications is to select a pump with a good volumetric efficiency. This equates to a pump that is not too big for the application and one that is operating with very little slip. Ways for reducing slip in progressing cavity pumps have been previously discussed. Pumps sized in this manner will have excellent repeatability and will perform quite predictability. It is also a good practice to use variable speed drives with metering pumps. This permits the pump speed to be changed as needed to accommodate changes in fluid viscosity and to compensate for pump wear.

Since the rheological properties of viscous fluids often change in response to system changes, viscous fluids normally present unique pumping opportunities. Since viscosity is that property of a fluid that causes the fluid to resist flowing, the higher the viscosity of a fluid, the more it will resist flowing. Water and light oils are examples of low viscosity fluids. Molasses is an example of a high viscosity fluid.

As the rotor in a progressing cavity pump rotates, fluid flows into the two cavities opened and closed with each revolution. With high viscosity fluids, there is a speed of rotation for the fluid where the fluid is not able to flow into the elements fast enough to fill the cavity completly. When this occurs, the pump is operating at less than 100 percent volumetric efficiency. Operating at speeds greater than this threshold speed results in a further reduction of the volumetric efficiency. Progressing cavity pumps are commonly operated at volumetric efficiencies as low as 50 percent when pumping high viscosity fluids, without adversely affecting the pump or the fluid. Over the years, data have been generated based on tests that permit a determination of volumetric efficiency for a given pump speed and fluid viscosity. These data can be used also to determine the maximum speed at which a pump can operate for a given viscosity and still have 100 percent volumetric efficiency.

In addition to influencing the speed at which a pump can operate and in turn the volumetric efficiency, fluid viscosity also affects slip, thereby affecting the size pump to be selected. The more viscous a fluid is, the less slip there will be for a given pressure. Fluid viscosity also has a significant effect on the power required, which also will affect the pump configuration. Being able to define accurately the fluid viscosity, understand how the viscosity of the fluid may change for different pumping conditions, and how this change will affect pump performance, can be critical to proper pump selection and operation.

The viscosity of a fluid can be determined with a number of commercially available instruments. Most fluids are shear sensitive, that is, the viscosity of the fluid will change when sheared, or agitated. Although the viscosity of most fluids will decrease with an increase in shear rate, there are exceptions. The viscosity of some fluids will increase with increasing shear rate. Some fluids also change viscosity in response to the length of time they have been sheared. A representative plot of viscosity vs shear rate is presented in Figure 5. Just how the viscosity of one fluid varies with the shear rate is also shown. Therefore, it should be obvious that obtaining viscosity readings as a function of shear rate is essential to accurately defining the viscous properties of a fluid.

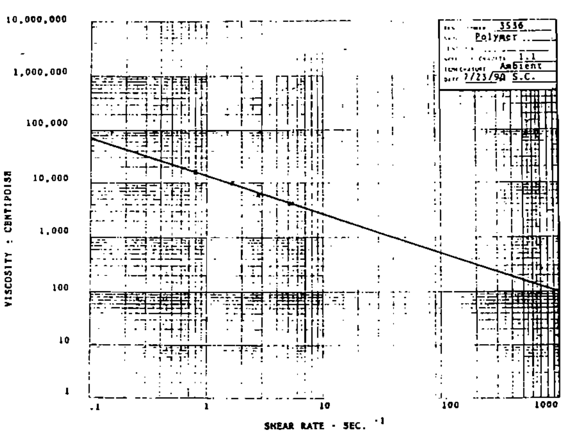

Figure 5. A Plot of Fluid Viscosity Vs Shear Rate is Required in Order to Accurately Size Pumps and Equipment for Non-Newtonian Fluid Applications.

As previously mentioned, the shear rates in progressing cavity pumps are typically low, compared to other types of pumps. However, even at these low shear rates, fluids passing through the pumps will be subjected to some shearing. The viscosity of the fluid as it passes through the pump will be different from the viscosity in other parts of the system. Unfortunately, most viscometry equipment obtains viscosity readings at lower shear rates than those a fluid is normally subjected to by a pump or piping. This results in apparent viscosity readings, which are typically higher than the actual fluid viscosity as it passes through the pumps. The "Xs" on the plot of viscosity vs shear rate shown on Figure 5 are the actual viscometer readings. Selecting pumps or other equipment based on these readings, without extrapolating these data to the shear rate ranges the pumps usually operate in, can result in the selection of pumps larger than actually required. With a plot of viscosity vs shear rate, the actual viscosity of the fluid as it passes through the pump can be determined, and the optimum pump for the application can be selected.

The process of properly selecting a pump for a viscous fluid is an iterative process that is quite involved and was the subject of a paper presented by the author at the 12th International Pump Technical Conference in England in 1991. The best way to examine the effects of viscosity data on pump selection is with an example.

The data provided in Figure 4 are for a pump selected based on the apparent viscosity readings shown in Figure 5. The data provided in Figure 6 are for a pump selected based on extrapolating the viscosity readings to shear rates corresponding to those in the pump. This resulted in the selection of a smaller pump with a substantially lower power requirement. Also, note the difference in slip, pump speed, and volumetric efficiency resulting from the different viscosity values. It is obvious from this example that the more information available on the rheological properties of the fluid, the better the pump selection will be.

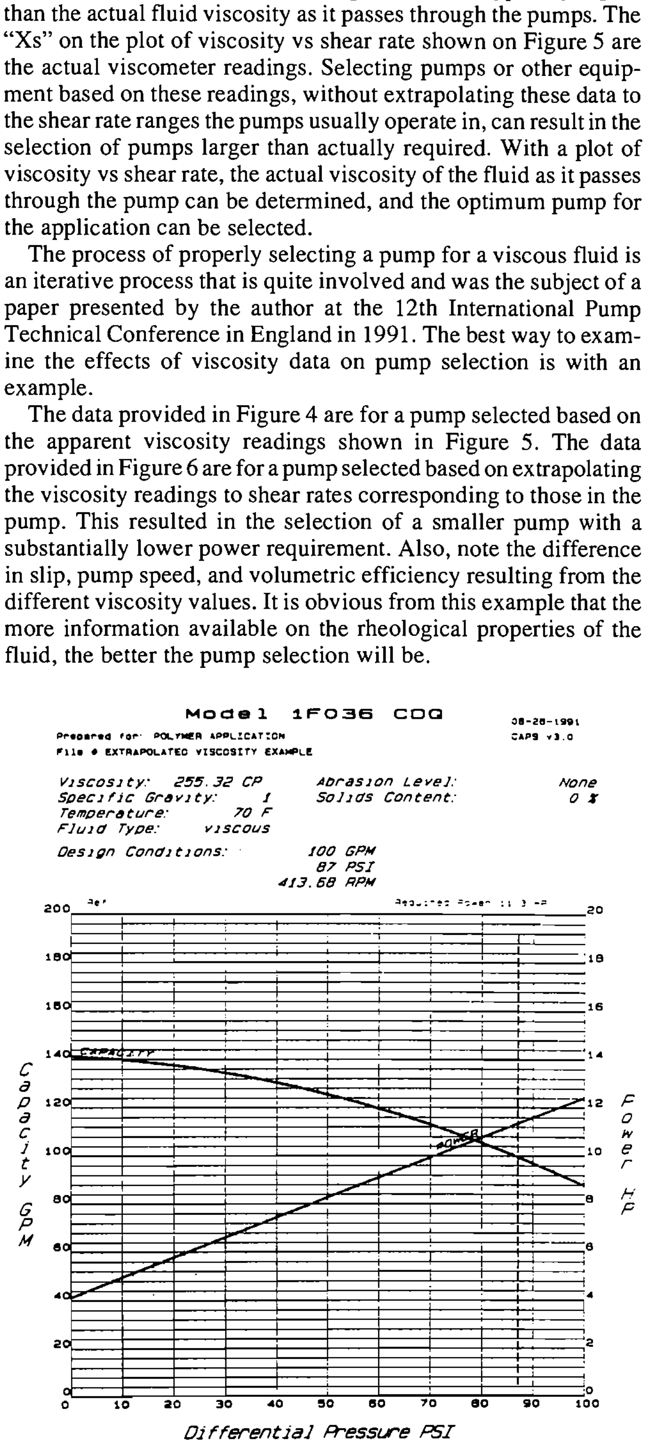

Figure 6. The Performance Data for a Pump Selected to Handle the Viscous Fluid Shown in Figure 5 Indicates the Viscosity of the Fluid As It Passes through the Pump Will Be Relatively Low.

Another fluid property that can have a profound effect on the pump selected is the degree of abrasion in the fluid. Unfortunately, determining the abrasive characteristics of a fluid is subjective at best. Although there are systems for determining the abrasive properties of solid particles, attempting to use these systems to quantify the abrasiveness of slurries and solid particles suspended in fluids has not been successful. Therefore, in order to permit the best pump selection for pumping an abrasive fluid, it is helpful to have some understanding of the mechanics of the wear process in progressing cavity pumps.

Abrasive wear in a progressing cavity pump is generally a combination of several phenomenon that occurs between a rotor and stator. The first involves the rubbing velocity between the rotor and stator. Some pump manufacturers have altered the rotor and stator geometry in an effort to reduce the rubbing velocity and thereby reduce wear. This can marginally improve life in specific applications. However, it is not the panacea some had hoped for, primarily because the predominate wear mechanism in many applications is related more to slip than to rubbing velocity.

Since rubbing velocity for a given rotor/stator geometry is directly proportional to pump speed, it is obvious that reducing pump speed will result in lower rubbing velocities and reduced wear between the rotor and stator. The proportion between pump speed and rotor/stator life depends on a number of characteristics of the abrasive particles. Therefore, the proportion will generally be different for different fluids.

It also should be noted that it is possible to reduce the pump speed to such a low value that the abrasive particles will fall out of suspension and accelerate wear. This situation is normally only encountered with heterogeneous slurries containing heavy solids compared to the fluid media.

The second phenomena in a progressing cavity pump that contributes to wear is associated with the centrifugal force of the rotor. This phenomena is also closely related to the wear associated with rubbing velocities. Years ago, it was a common practice to bore the larger diameter rotors in an effort to reduce the rotor weight. This reduced weight was thought to reduce the vibrational forces resulting from the mass of the rotor rotating eccentrically in the stator. The reduced weight was also thought to reduce wear in abrasive applications. Actual tests revealed the reduced weight had only marginal effect on the vibrational forces, due in part to the relatively low speed of rotation at which progressing cavity pumps typically rotate. Tests also failed to verify that the lighter rotors resulted in significantly improved stator life. Therefore, the effect of centrifugal force on the wear in a progressing cavity pump in most abrasive applications is relatively insignificant.

The most significant abrasive wear mechanism is associated with slip. From previous discussions, it is obvious that the more internal leakage there is with an abrasive fluid, the more the wear is going to be. Therefore, the preferred solution to decreasing wear associated with slip in an abrasive application is to increase the number of stages, thereby decreasing the differential pressure per stage and reducing the slip.

Another common practice is to use an oversize rotor as previously discussed to reduce the amount of slip. Generally, increasing the number of stages will result in a greater improvement in life than the use of a tighter rotor-stator fit. In extreme cases, reducing the speed and increasing the number of stages is required to increase significantly rotor and stator life.

In many abrasive applications where the differential pressure is low and slip is not significant, using a softer stator elastomer will provide the best life. One thing to be considered before using a softer elastomer is that slip will increase with a decrease in the hardness of the elastomer. Therefore, to avoid increasing the amount of slip when a softer elastomer is used, an oversize rotor is often recommended.

EXAMPLE

An example will demonstrate the need for accurately defining the fluid properties and the effect these properties have on pump selection.

Consider a polymer application where a maximum flowrate of 24 gpm at a total differential pressure of 60 psi was specified. The viscosity of the polymer was specified to be 4000 to 14000 centipoise. From experience with polymers, the viscosity was known to be grossly overstated and an actual plot of viscosity vs shear rate is shown on Figure 5. The specified values of 4,000 to 14,000 centipoise cover the range of recorded viscosity readings. In reality, the viscosity of the fluid in the system would be much lower, as indicated by the actual viscosity curve.

A computer selection of acceptable pumps for this application, using the lowest recorded viscosity reading of 4000 centipoise, resulted in the pump selected, as shown in Table 1. This pump is operating at 935 rpm and has a power requirement of 7.3 hp. The shear rate in the pump at this speed is 724 sec-1 and a review of Figure 5 at this shear rate indicates the corresponding fluid viscosity would be approximately 125 centipoise. The 4000 centipoise viscosity value specified obviously is not correct for this application.

Using the viscosity data on Figure 5 and an iterative process, the actual operating conditions for the polymer shown on Figure 5 are shown on Table 2. As indicated in Table 2, the correct pump speed would be 528 rpm and the correct power requirement would be 2.5 hp. This is a substantial reduction in speed and hp.

In this particular application, the company was able to convince the customer that the calculations and selections were correct, only by agreeing to test several of the pumps with the polymer prior to shipment. The tests verified the calculations and selections and the pumps have performed flawlessly.

Although most polymers are not abrasive, assume that the polymer in this application was classified as having "medium"

Table 1. The Performance Characteristics for a Pump Selected to Pump 24 GPM of a Fluid with an Apparent Viscosity of 4,000 Centipoise against a 60 PSI Differential Pressure.

Selected Pump	
Specifications	
Capacity	24 gpm
Pressure	60 psi
Viscosity	4,000 cp
Abrasion	none
Performance	
Speed	935 rpm
Slip	1.55 gpm
Shear rate	724.5 sec^{-1}
Power required	7.3 hp

Table 2. Performance of the Same Pump as Shown in Table 1. The viscosity has been corrected to show the actual viscosity obtained from Figure 5 corresponding to the shear rate in the pump.

Selected Pump	
Specifications	
Capacity	24 gpm
Pressure	60 psi
Viscosity	200 cp
Abrasion	none
Performance	
Speed	528 rpm
Slip	1.74 gpm
Shear rate	409 sec^{-1}
Power required	2.5 hp

abrasiveness. Data are provided in Table 3 about the pump selected for 24 gpm at 60 psi of the polymer shown by Figure 5, assuming medium abrasion. Due to the abrasiveness of the fluid, a larger pump operating at a lower speed was selected. As indicated in Table 3, the operating speed of the larger pump is only 249 rpm and the power required is 2.6 hp. It should be noted the slip in this example is only 2.67 gpm compared to a produced flow of 24 gpm. The slow speed and slip should result in many hours of maintenance free operation.

CONCLUSION

Although progressing cavity pumps appear to be complex, they are actually quite simple. As suggested by the discussion of several typical areas of application, obtaining as much information as possible about the fluid is essential to properly selecting any pump. Proper interpretation of this information and an understanding of progressing cavity features and characteristics will permit the correct selection of a pump for any application. In those cases where several pumps would appear to be suited for an application, selecting the pump with the least amount of slip will normally result in the most satisfactory operation.

Table 3. When the Fluid Specifications of the Pump Shown in Table 2 Is Changed from No Abrasion to Medium Abrasion a Larger Pump Is Selected.

Selected Pump	
Specifications	
Capacity	24 gpm
Pressure	60 psi
Viscosity	325 cp
Abrasion	medium
Performance	
Speed	249 rpm
Slip	2.67 gpm
Shear rate	189 sec^{-1}
Power required	2.6 hp