

RECIPROCATING COMPRESSOR VALVE RELIABILITY IMPROVEMENTS

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the effects of pulsations and valve dynamics on compressor performance and reliability.



Derek Woollatt has B.Eng and Ph.D degrees from the University of Liverpool, U.K. He spent three years lecturing on thermodynamics and fluid mechanics at the University of Manchester and 30 years in industry with Worthington and Dresser-Rand working on the development of reciprocating engines and compressors. Dr. Woollatt has concentrated on development testing and issues related to compressor and engine performance. Over the last 20 years, his work has

included the development of compressor valves and methods to select them for specific applications. Improving compressor reliability and efficiency have both been addressed, but the primary focus has been designing valves that will give reliable service in the harsh conditions experienced in process and separable compressor applications.

ABSTRACT

The primary improvements made to compressor valve reliability over the past several years are covered. The topics include seat, stop plate, element and spring design and will discuss the advantages and disadvantages of various valve configurations.

INTRODUCTION

There is perhaps no single element that affects reciprocating compressor reliability more than the valves. There are certainly

parts that are more difficult and costly to maintain, but none are more susceptible to gas conditions and process upsets than the valves. There is also nothing as frustrating than to be unable to run a critical compressor because a relatively inexpensive component continually fails in operation. Because of this, a great deal of time and effort has been expended over the past several years to improve compressor valve reliability. These enhancements have been made in body, element and spring design along with the materials used in the production of these parts.

There has been increased interest in poppet valves for process applications in the past five years. This is primarily due to several unique advantages found in this valve design. Poppet valves are compared to the more traditional process valves, where it is applicable.

FACTORS AFFECTING VALVE RELIABILITY

There are a wide variety of influences that the compressor valves must surmount during an acceptable run period. Liquids, debris, pulsations, and corrosives must all be overcome with proper selection of valve type, lift, spring and materials. This can be a major project, especially when many of these influences can not be accurately predicted, even with modern methods. The task, therefore, is to optimize the design of the seat, stop plate, element and spring such that the effects of these factors are minimized. This can be accomplished with geometry, manufacturing techniques, or materials. The optimization of the design of these components, and the advances made in recent years, will be discussed in the following sections.

Because refinery and chemical process compressors offer the most challenging design obstacles, the majority of the design improvements, and the resulting subjects fall under these applications.

SEAT AND STOP PLATE DESIGN

There are a wide variety of valve types used in reciprocating compressors. The three most common are the ported plate (often used with a damping plate), ring and poppet valve. Although there have been many other valve designs (channel, strip, etc...) used, these three are considered the most common in recent times. The general element/spring configuration of each of these valve types is shown in Figures 1, 2, and 3, respectively.

Although the basic seat and stop plate design concepts have remained primarily unchanged for many years, there have been great improvements in the design methods used to predict the bending and shear stresses in critical areas. The use of finite element analysis for examining these stresses has allowed the

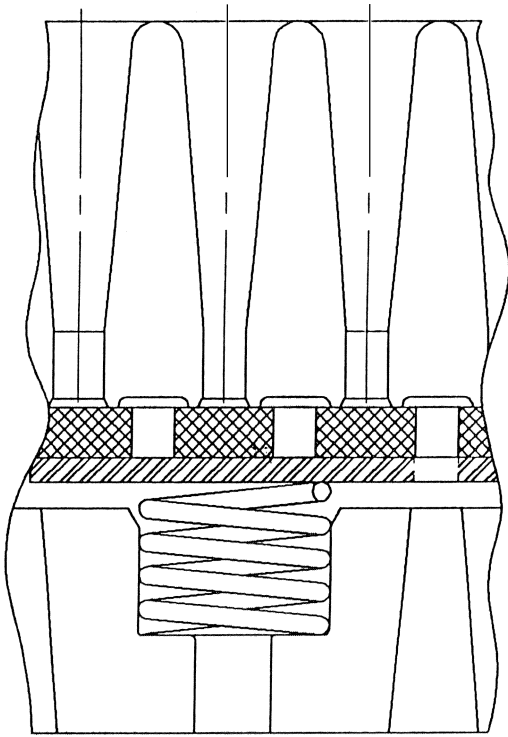


Figure 1. Plate Valve Internals.

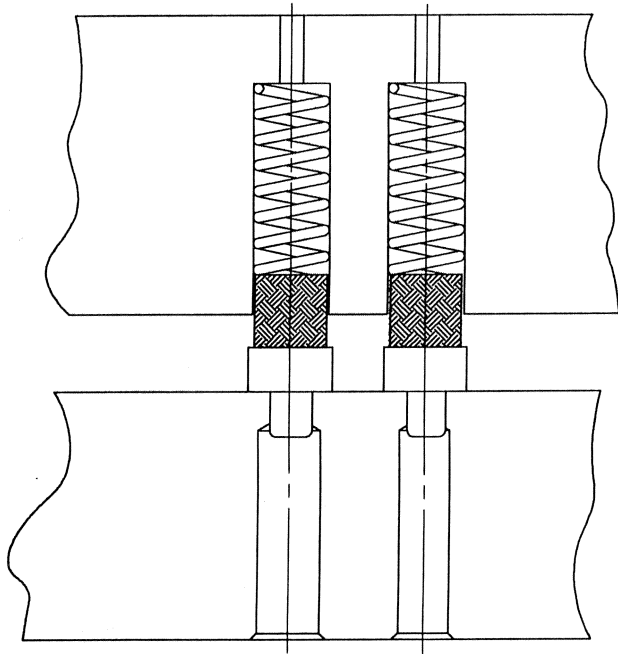


Figure 2. Ring Valve Internals.

modern engineer to adjust the location of elements and flow holes to optimize thicknesses and material selection.

Seat and stop plate failures are very rare under normal conditions. In the past this was accomplished by using conservative seat and stop plate rim thicknesses. This conservative approach was bred by a lack of refined stress analysis capabilities. FEA has allowed for more accurate stress prediction and has led to thinner seats and stop plate rims. Although these thickness

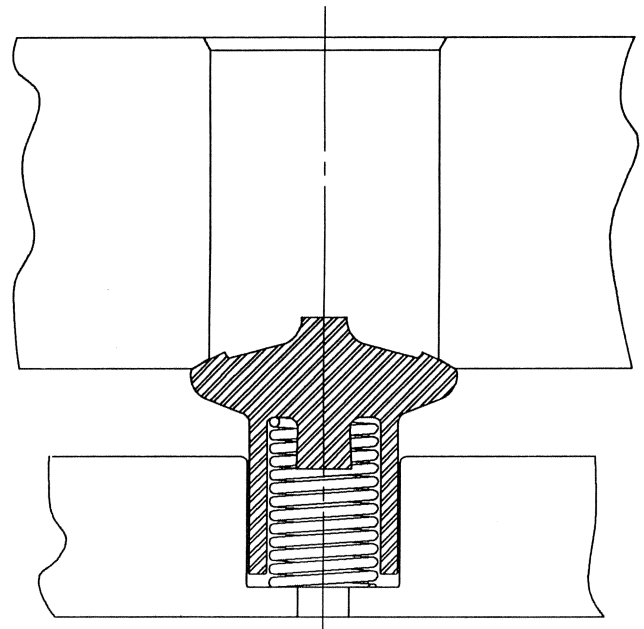


Figure 3. Poppet Valve Internals.

values do not directly affect the reliability of the valve, it does contribute two important performance attributes that are worthy of mention. First, thinner seats reduce the internal clearance of the discharge valves. This allows compressor manufacturers more flexibility in cylinder design and can eliminate concerns over lost capacity due to excessive clearance when installing a new valve design in an existing compressor cylinder. Second, reduced stop plate rim thickness allows the valve engineer to use more of the outside section of the valve for elements. This increases the flow area of the valve and leads to reduced horsepower.

On the reliability side of body design, there are several crucial aspects that need to be taken into account beyond tensile and yield strength. Corrosion resistance is often a factor, even when initial gas analysis does not indicate the presence of such constituents. Upset conditions can occur from time to time, resulting in slow, but constant, degradation of material properties. Therefore, seat and stop plate materials must be selected to combat the effects of sulfides and chlorides, while still maintaining high tensile and hardness properties. There are a variety of materials available that perform well in corrosive environments, are readily available, and do not result in adding unreasonable cost to the components. Ductile iron, for example, performs well in many corrosive atmospheres in lubricated cylinders and offers good strength and hardness characteristics. In cases where there are extremely high levels of corrosives, more exotic stainless steels are sometimes required. These materials should only be used when absolutely necessary, however, since they can greatly inflate the cost of manufacturing the component. For the most part, experience has led to the criteria for determining if a more exotic material is required.

Seat and stop plate hardness is often overlooked, but is very important to resist excess wear in the seating areas and in the spring pockets. Even nonmetallic elements have been known to wear into the seat. This is especially true when dirt and debris are present. These impurities can act as an abrasive and slowly wear into the seating surface. As the wear becomes greater, the travel of the element (lift) increases by the same amount. This results in running a valve at a higher lift than it was designed and typically will lead to element failure. Spring pocket wear is even

more likely, as the spring is almost always harder than the stop plate and has a tendency to rotate during operation. This wear has been combated in the past by using a spacer in the bottom of the spring pocket to act as a buffer between the spring and stop plate. This can lead to more problems than it solves, however. If this spacer is left out of the pocket when the valve is assembled, the spring length and resulting forces are severely affected, and in some cases, eliminated entirely. As discussed in a later section, valve springing is probably the most important aspect of reliable compressor valve design, and any alteration affecting the forces applied by the springs will usually lead to premature valve failure. Selecting stop plate materials that are of sufficient hardness to combat wear in the spring pockets is extremely important.

It is usually desirable to design the through holes in the seat and stop plate as large as possible to allow dirt, liquids and other incompressible substances to pass more freely through the valve. This can often be difficult since increasing the width of the valve plates also increases the bending stress in the plate and reduces the number of plates that can be used, thus decreasing the valve flow area. It also increases the contact force on the seating surface. The bending stress can be reduced by making the plates thicker, but this increases the plate mass, which can adversely affect element motion and increases the clearance volume of the stop plate, decreasing compressor capacity. The decreased flow area due to using fewer plates can only be offset by increasing the lift. This will almost always adversely affect valve reliability. The increased contact force can only be offset by increasing the sealing area. This further reduces the valve's flow area and hence the compressor efficiency. This makes plate, channel and ring valves very sensitive to damage and clogging in dirty services.

Poppet valves offer much more generous porting by using a large, round element that seats on a single, large hole. This makes it a more reliable design when dirt and liquids are present. This advantage, though logical, was not fully realized until poppet valves were applied in process applications in the past few years.

ELEMENT DESIGN

Each of the element designs shown in Figures 1, 2, and 3 have undergone numerous changes over the past 10 years. The most critical change is the constant development of better materials for use in these areas, especially nonmetallic. Before the 1980s, the primary element materials were stainless steel (of various grades) and, to a lesser extent, glass filled Nylon. The stainless steel materials offered excellent temperature and pressure application windows, but lacked the impact properties of a nonmetallic material. They also had a tendency to damage the cylinder bore and liner if the plate failed and left the valve. Nylon had much better impact properties but was limited to 250°F, and swelled and lost tensile strength in operation due to water absorption. Work on the composition and molding of the Nylon improved the situation, but the material remained inherently limited.

The need for a more advanced polymer for this application led to the development of PEEK (poly ether ether ketone) for compressor valve elements in the mid 1980s. This revolutionized compressor valve design. It offered a material that had excellent impact and corrosion resistance properties in temperatures up to 400°F with very little water absorption. This was a major event in the development of a more reliable compressor valve. In the past 10 years, literally hundreds of new materials have been developed and tested in an attempt to find one that will outperform PEEK in compressor valves. Despite these efforts, PEEK still reigns as the best nonmetallic material option available for compressor valve elements to date.

Although PEEK has been used successfully for quite some time, the quality of the finished elements has continued to improve. PEEK is very difficult to manufacture into valve elements due to a variety of obstacles. The molding temperature of PEEK must be high because of the high melting point, and is not far below the temperature at which it oxidizes. Stagnant flow areas where the material may stay at high pressure for a longer time than necessary should be avoided. The viscosity is also high at the molding temperature and the high pressures and shear forces that are required result in consequent generated heat if the molds are not gated properly. This can also occur if the molding pressures are too high in an attempt to fill the mold fast to prevent voids as the PEEK cools and solidifies. Further, the mold temperature must be relatively high to allow the PEEK to cool slowly enough to allow optimum crystal growth. If the material cools too fast the part will contain amorphous material and the impact strength will be low. It is essential that the melt and mold temperatures and the injection pressure be correctly chosen and accurately controlled so that the mold fills properly and crystal growth is optimum, but the melt temperature is never high enough for it to start oxidizing. Oxidized (charred) PEEK is dark brown or black as compared to the normal tan, and results in severe degradation of the mechanical properties of the material. In Figure 4, the effect of char on the strength of PEEK is shown. It is very important that char is minimized in valve plates, especially in impact areas. As the use of PEEK resin has expanded over the years, the molding processes have been refined to greatly reduce this problem. It should remain a major inspection point, however, and only natural colored resins should be used, to ensure that coloring does not cover a char problem.

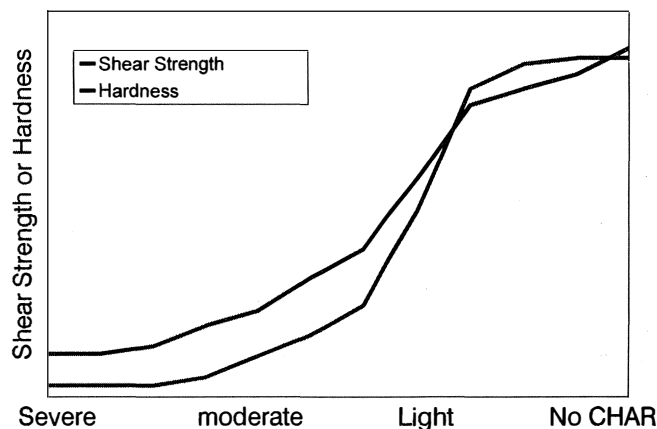


Figure 4. Effect of CHAR on Properties.

Even if quality processing of the elements is achieved, it is crucial that the proper resin is used in manufacturing. There are two grades of PEEK resin available. Both are commonly used in plate and poppet manufacturing but the lower viscosity grade is considerably inferior for this application. This lower density 150GL or "easy flow" grade of PEEK was introduced into the marketplace because it is much easier to mold than the standard, denser, 450GL version. At first glance, this option appears viable, since the tensile strength is higher than the 450GL grade, even at 350°F.

Impact properties suffer gravely, however (Figure 5). The difference between these grades can not be identified visually, but the distinction will be quickly made based on the reliability of the valve element. Tests in a valve endurance test rig were done when the 150GL material was first introduced. These tests showed that the valve life in some applications would be very

RESINMAKER'S MECHANICAL TEST RESULTS

<u>PEEK Grade</u>	Tensile	Notched
	Strength	Izod,
	<u>psi</u>	<u>ft-lb</u>
HITEMP Base	22,800	2.1
Easy Flow	23,800	1.8

Figure 5. Resinmaker's Mechanical Test Results.

low and the material was eliminated from consideration as an element material.

Another way to reduce the cost of PEEK plates and poppets is to regrind the waste from the gates and machining and add it to the material that will be used to mold the next batch of plates. Up to 50 percent regrind has been recommended. This works well for low stress applications, but the temptation must be avoided in the manufacture of valve plates. Tests in a Valve Endurance Test Rig showed that plates containing regrind have very short life compared to plates made from 100 percent virgin material.

The impact of the element on the seat and stop plate is determined as part of the valve dynamics calculation described in a later section. Experience has provided "rule of thumb" values for the maximum allowable impact velocities for different valve designs. Special designs using mass damping plates and patented scalloped sealing plates are used if the application requires that the valve run with impact velocities greater than allowable in a standard, low impact, valve. This usually occurs only in high speed (>1000 rpm) compressors. To optimize the plate design, it is necessary to calculate the stresses caused by the impact. The stress patterns in a valve plate at 0, 1, 2, and 3 microseconds after impact on a point based on finite element analysis is shown in Figure 6. The stress concentrating effect of the holes in the plate can be seen. With this tool, the size and location of the hole can be optimized to provide long life with good performance, even under high impact conditions.

SPRING DESIGN

Proper springing is arguably the most important aspect of compressor valve design. In addition, the design of compressor

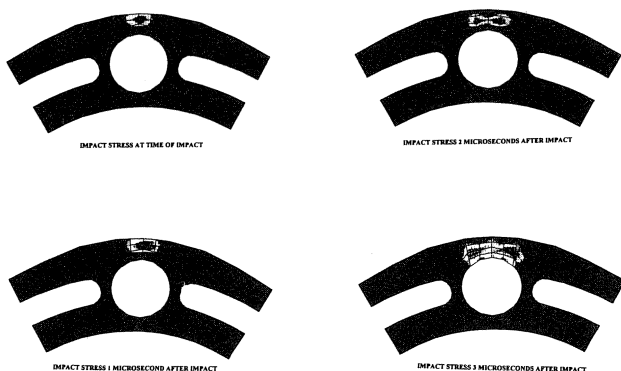


Figure 6. FEA of Impact Stresses in a Valve Plate.

valve springs goes far beyond simply opening and closing the valve. Proper selection of material and design of acceptable operating stresses based on those materials is just as critical.

If no corrosives exist, a variety of materials with excellent tensile and torsional properties can be effectively used. Chrome silicon steel and music wire offer exceptional tensile strength, although normal operating temperatures of many compressors limit the use of music wire. Chrome silicon steel has been used in low levels of corrosives with good results in lubricated compressors. When higher levels of corrosives are encountered, however, spring material selection becomes much more difficult. Materials are available that can resist these corrosive environments but many of these materials have lower allowable fatigue stress levels than chrome silicon steel and none of the materials are completely resistant to both chlorides and hydrogen sulfide.

A number of corrosion resistant alloys have become popular in recent years. Inconel X-750, Hastelloy C-276, elgelloy and MP35N have replaced 302 stainless steel and 17-7 PH as the alloys of choice for corrosive atmospheres. Each of these materials has limitations, however. Inconel has excellent resistance to sulfides, but can be attacked by chlorides, even in parts per million, if water is present. MP35N and elgiloy also have excellent resistance to sulfides and resist chlorides better than Inconel, but not as well as Hastelloy C-276. Hastelloy is the material of choice to resist chlorides but is not as resistant to sulfides. If both chlorides and sulfides are present, a compromise is necessary. In addition, inconel and Hastelloy have low acceptable fatigue stresses and designing a spring with good fatigue life that provides adequate spring force and fits in the space available can be difficult or impossible in some applications. The valve designer needs to have accurate information on the corrosives that will be present during normal and upset conditions so that the best material will be chosen.

When designing compressor valve springs, it is critical that acceptable operating stresses are realized. It is not sufficient to simply design the initial and final stresses within material limits. There are other considerations that must be appraised. One of the most critical of these is spring surge effects. Spring surge is caused by instantaneous deceleration of the spring (when the element impacts the seat and stop plate) and results in amplified stress concentrations along the wire length. There is yet to be a proven method of predicting spring surge effects on compressor valve springs. Therefore, the most effective way of taking these effects into account, is to design the springs with very conservative stress levels.

Cylindrical spring stress is affected by the force the spring exerts, the wire diameter used and the mean outside diameter. The total spring force required to close the elements before top dead center (valve motion will be discussed in the next section) is dictated by a large number of factors. These include, but are not limited to, the number of springs under each element, the mass and face area of the element, the number of valves in the cylinder, the swept volume of the cylinder, and the operating conditions. Designing these factors in favor of lower required force, and resulting stress, can be difficult. Increasing the number of springs, for example, can help lower the required force of each individual spring, but takes away from the flow area available in the stop plate, limiting how far this method can be taken. Needless to say, depending on the application at hand, the required spring force may be high despite the efforts of the engineer to design the valve otherwise. It is necessary, therefore, to concentrate on the geometric configuration of the spring in order to keep the stress at a conservative level. Although increasing the OD of the spring also elevates the torsional stress, minimizing the wire diameter has a much greater effect because

it is a cubed term. As a result, increasing the OD and free length in order to utilize a larger wire is often an effective method to reduce stress. Designing a spring in this way will usually result in a more conservative design.

The maximum spring stress is calculated at the final spring length, where the force is the highest. Valve designs that utilize a button between the plate and spring (Figure 2) can result in final spring lengths much lower than predicted. This is caused by the button continuing to travel, even when the plate has impacted the stop plate. Depending on the opening velocity of the plate, the kinetic energy of the button can be very high and can overcome the potential energy of the spring, traveling to a point where the final spring stress exceeds the allowable stress for the material or initiating coil to coil contact. The adverse effects of coil clashing has been known for some time and are well documented in most spring design handbooks. Button overshoot is a phenomena that must be taken into account when using a button in valve design. Since valve opening impact velocities are extremely difficult to predict and can be severely effected by pulsations, eliminating the button in compressor valve designs is attractive.

Spring buttons are used primarily to protect the spring. When using valves that have a lift that is greater than the wire diameter of the spring, there are well founded concerns about the spring wire catching on top of the spring pocket. Since typical plate valve springs have wires 0.025 to 0.045 in, this is extremely common.

The introduction of poppet valves (Figure 3) in process applications has eliminated many spring design concerns and has resulted in valves which are much less susceptible to spring failure due to fatigue. Since this is one of the most frequent forms of valve failure, the outcome is a much more reliable valve. Due to the poppet valve's unique design, the springs have a much higher free length and outside diameter than conventional plate valve springs. This is possible because the poppet encompasses the spring, eliminating the possibility of the spring catching on top of the spring pocket. Since each poppet is typically an inch or greater in diameter, the spring OD is also larger than most plate valves. Where plate valve spring wire diameters typically range between 0.025 and 0.045 in, poppet valve springs can utilize wires as large as 0.065 in. Although larger wires result in higher spring rates, and resulting forces and stresses for a given compressed length, this can be taken into account in the poppet valve. Poppet valve springs have higher free and final lengths are not limited by the depth of the spring pocket because of the geometry of the element. When the engineer is working with a spring design such as this, the free length can be adjusted to obtain the best combination of wire diameter, spring rate and resulting force for low stress. When dealing with less flexible free lengths, as is usually the case with plate valves, small wires become a necessity to avoid taking the spring to solid height in operation.

PREDICTING VALVE MOTION

Assuming that the springs are designed with acceptable stress levels, valve motion becomes the most critical aspect of valve design. The most common cause of plate or poppet breakage is late element closing. The pressure drop across the valve opens the elements but it is critical that the springs close them. If the elements are not closed (against the seat) at top dead center (TDC), the gas force, resulting from the reversed piston motion, will slam them closed, increasing the impact velocities considerably. Therefore, the first criteria for valve lift and spring selection is to have sufficient spring force to close the elements before TDC.

There are a variety of analysis programs that are used throughout the industry for the purposes of predicting valve motion.

Although the sophistication of these programs has improved greatly over the past several years, cylinder and passage pulsations continue to be difficult, if not impossible, to accurately take into account when predicting element motion and impact velocities.

The best scenario is to limit the pulsation amplitude at the valve to an acceptable limit based on API standards. It is usually not sufficient to simply analyze the pulsations at the bottle nozzle as the amplitude will likely increase significantly at the valves. High pulsations at the valves can cause the elements to stay open much longer than predicted and slam closed or simply increase the opening and/or closing impacts beyond the critical values defined by the element material properties. It is also important that the valve creates a sufficient pressure drop. It has been learned, through field experience, that valves that have a pressure drop which is 0.5 percent or less of the line pressure are much more likely to have their motion affected by, or even controlled by, pulsations. By using this knowledge, a selection can be made that will resist pulsation effects just as the proper materials will minimize corrosion concerns.

Another factor to consider when examining element motion is the effect of oil on valve motion. Excess or heavy oils, or oils that are compounded with animal fats can create very high viscous adhesion forces between the valve plates and the seat and stop plate. This adhesion is one more force that the springs must overcome in order to properly close the valve before TDC and can delay the opening of the valve, increasing the stop plate impact velocities. Laboratory tests have been conducted in an attempt to qualify the effects of oil on valve motion, but the large variety of oil types, combined with the practice of over lubricating compressor cylinders, make these tests limited in value. Suffice to say, excessive oil can often cause extreme valve reliability concerns. Since most modern valves are designed to operate in both lube and nonlube service, lower lubrication rates and lighter oils are much preferred, as far as the valves are concerned. This brings up another major advantage of using poppet valves. Since the contact area between the poppet and the stop plate and seat is so much smaller than that of a plate valve, the resulting adhesion force is also lower. Because of this, oil effects on poppet valve motion is of much less concern. This allows compressor operators to concentrate on the lubrication requirements of the other cylinder components, without adversely affecting their compressor valves.

The effects of sticktion on the seat are difficult to measure in the field, but can be estimated from pressure/volume cards. A pressure/volume card from a refinery compressor running on a fairly viscous, but not compounded, oil is shown in Figure 7. The suction valves removed from this compressor had a heavy coating of oil but showed no signs that the oil was thickened by temperature, dirt contamination or other causes. The calculated diagram, without seat sticktion, from the valve dynamics program is shown in Figure 8. It will be noted that the overshoot of pressure at valve opening is larger on the measured diagram. By increasing the sticktion factor in the calculation, the pressure/volume card shown in Figure 9 was obtained. The authors assume that the sticktion is correctly modeled when the pressure overshoot calculated agrees with that measured in the field. In this case, the calculations showed that sticktion effects increased the impact velocity on the stop plate by a factor of 3.

Since field conditions vary to such a great degree, choosing a spring which closes the valve a little early will often eliminate possible reliability problems caused by late closing, be it from pulsations, sticktion or a consolidation thereof. This may cause the valve to experience some flutter, but this is of very little concern compared to plate closing. It is extremely difficult to predict the effect that valve flutter has on seat and guard impacts,

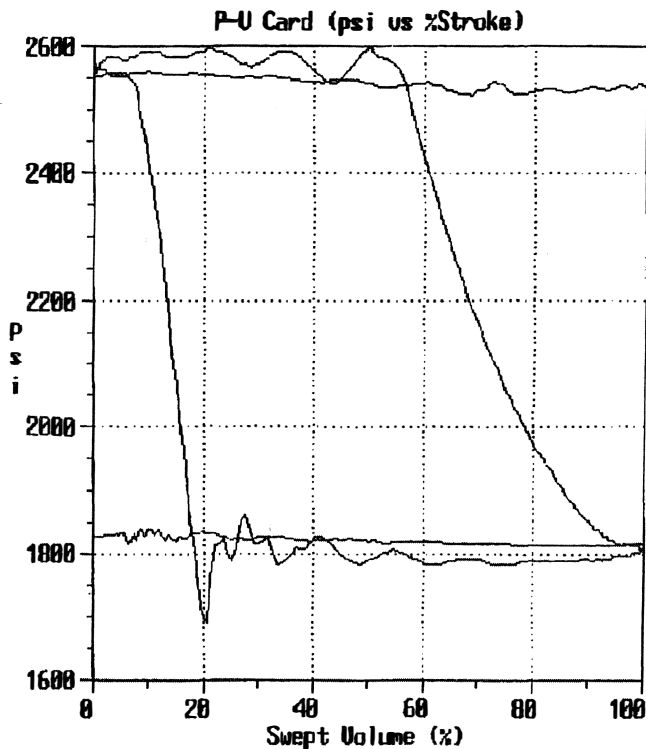


Figure 7. Measured P/V Card.

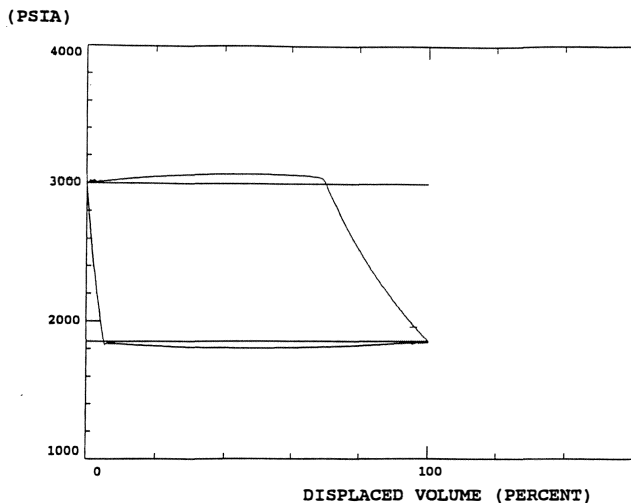


Figure 8. Predicted P/V Card.

but practical experience in this area tells us that flutter very rarely causes extreme reliability concerns. In fact, it is desirable to select a valve which shows some flutter at the end of the stroke on simulated curves. This gives an indication that the springs are overcoming the pressure drop across the valve enough before TDC to account for any pulsation effects not taken into account in the program. Since no computer program can truly simulate actual element motion, some conservatism must be included in the lift and spring selection. In most cases, this conservatism is in the form of element flutter at the end of the stroke.

CONCLUSION

Nobody will argue that reliability must be the foremost criterion for compressor valve design. The most efficient valve loses

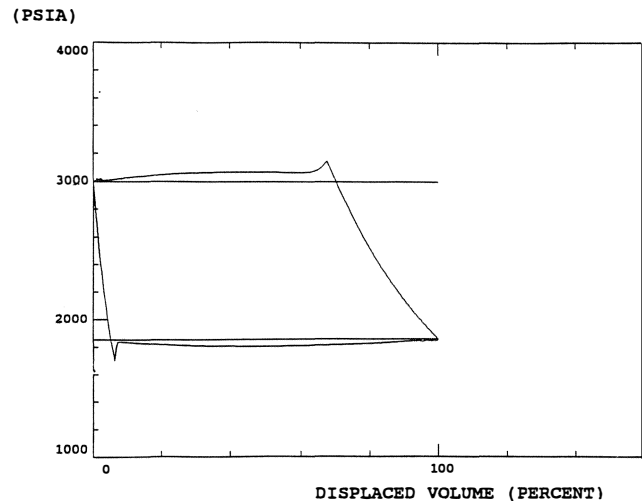


Figure 9. Predicted P/V Card with Increased Sticktion.

all of its advantages, if the compressor is not running because the valves have failed. Any valve design can be made to run reliably in clean, dry applications by simply adjusting the lift, spring and element material accordingly. In dirty, wet and corrosive atmospheres, valve design becomes much more difficult and selecting the proper valve type is critical.

All three common valve types (Figures 1, 2, and 3) are used in low speed (< 500 rpm), process applications. High speed applications often dictate the use of mass damping, which is usually a design feature of ported plate valves (Figure 3). This damping allows the valve to be designed with higher lifts, without increasing the opening impact velocities beyond their critical values due to the higher machine speed. The other valve types can be used, but the lift must be very low to reduce the impacts to an acceptable level. In most cases, this lift results in unacceptable valve areas and resulting cylinder efficiency. Mass damping is rarely required on the lower speed compressors. In these applications, nondamped valves such as concentric ring (Figure 2) and poppet (Figure 3) are more common. Poppets and plates will usually run equally well in dry, clean environments. Poppet valves have proven to be a much better choice for wet and dirty gases, however.

Poppet valves are much less susceptible to damage from gas impurities for a variety of reasons.

- The seats and stop plates have large flow holes to allow impurities to pass more freely through the valve.
- Because the springs are large in diameter, the vent holes in the spring pockets are also large, eliminating the collection of debris and oil, which can damage the springs.
- The flow path of the poppet valve results in less turbulence than a plate valve, and poppet seats and stop plates offer fewer corners and grooves for debris to gather.

Poppet valves also present the potential for much lower spring stresses if designed properly. Plate valves offer much less space to accommodate the springs, forcing the engineer to use lower free lengths and outside diameters. This results in smaller required wire diameters and higher resulting fatigue stresses.

In short, the introduction of poppet valves to process compressor applications has provided, perhaps, the greatest opportunity for improving valve reliability in many years. Although plate valves can be very reliable if properly designed and applied, poppet valves extend more flexibility in designing critical components and are less likely to be influenced by incompressible

substances and excess oil, which are unavoidable in many applications. Since all of the modern design techniques and materials discussed in this paper can be used with any design, the poppet seems likely to forge ahead in the years to come, as the valve of choice for reciprocating compressors.

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