CONTROLLING POSITIVE DISPLACEMENT PUMPS

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INTRODUCTION. The positive displacement pump is in some ways an even simpler device to control than the centrifugal pump discussed previously[1]. It has the same function, namely to provide the pressure necessary to move a liquid at the desired rate from point A to point B of the process. Figure 2-1 shows a "generic" process with a positive displacement pump (in this case a gear pump) connected to deliver liquid from A to B.

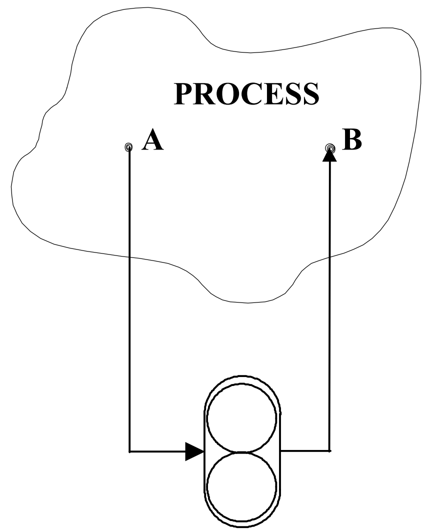

Fig. 2-1.A Gear Pump and a Process

There is a great variety of positive displacement pumps. They are divided into two broad categories: Rotary and reciprocating. From the controls point of view, however, they are all similar. Their characteristic curve is so simple that it is rarely drawn. It is essentially a straight vertical line, as shown in Figure 2-2. (For some reason PD pump curves are usually shown with the pressure and flow axis exchanged. I will not follow that convention in this article.) All are constant flow machines whose pressure rises to whatever value is necessary to put out the flow appropriate to the pump speed. If the discharge is blocked, the pressure will rise until something yields -- preferably a relief valve. Close examination of the curve shows a slight counter clockwise rotation. This is due to internal leakage. For positive displacement pumps the major cause of leakage is the small amount of reverse flow that occurs before a check valve closes and possibly past the check valve after it is closed. Leakage past the piston is negligible. Diaphragm operated PD pumps have no cylinder to leak past. Rotating PD pumps, such as gear pumps or progressing cavity pumps have internal clearances which permit a small reverse flow, called "slip" or "blowby". There is another reason why the curve may rotate to slightly lower flows at higher discharge pressures: The driver may slow down as the load increases. None of these have a significant affect in curving the slope of the characteristic enough that this slope can be used for control. For most practical purposes the slope is vertical. The system curve of the process is also shown on Figure 2-2. Its intersection with the pump characteristic defines the operating point.

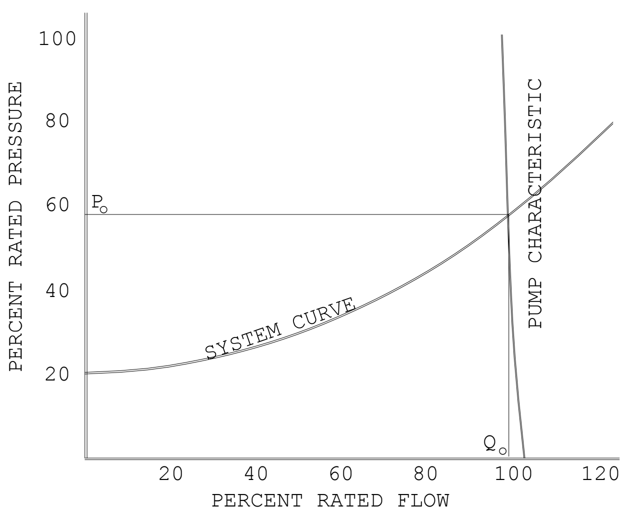

Fig. 2-2. Pump Characteristic and System Curve

As always, the process controls engineer has the responsibility of matching the capacity of a specific piece of equipment to the demands of the process at every instant in time. Rarely does the actual system curve fall exactly on the one used for design and selection. As with any two port device, there are three locations in which a control valve can be placed: On the discharge, on the suction, and as a recycle valve.

DISCHARGE THROTTLING. Discharge throttling does not work! Looking at the process from the point of view of the pump, discharge throttling rotates the system curve counter clockwise so that the modified system curve intersects the pump curve higher up. The additional pressure is dropped through the valve so that the pressure and flow to the process is (almost) exactly the same as before. The "almost" is due the small increase in internal leakage that results in an equally small reduction in flow. An increased wear rate and a shortening of the life of the machine are the only results of this approach. If the pump is seen from the point of view of the process so that the valve is considered part of the pump, the same result is obtained. To obtain a modified pump characteristic curve, the pump curve must be rotated clockwise around the intersection with the pressure axis. The problem is that this hypothetical intersection is far off the top of the operating range. It is the point where the pressure is so high that 100% internal leakage occurs. The machine would self-destruct from excess pressure if one were stubborn enough to attempt to find this point. The rotation of the curve can still be performed on paper and it amounts to a slight shift to the left. Shown in Figure 2-3, it is virtually identical to the unmodified curve. To cut a long story short, **you can't control a PD pump with discharge throttling**.

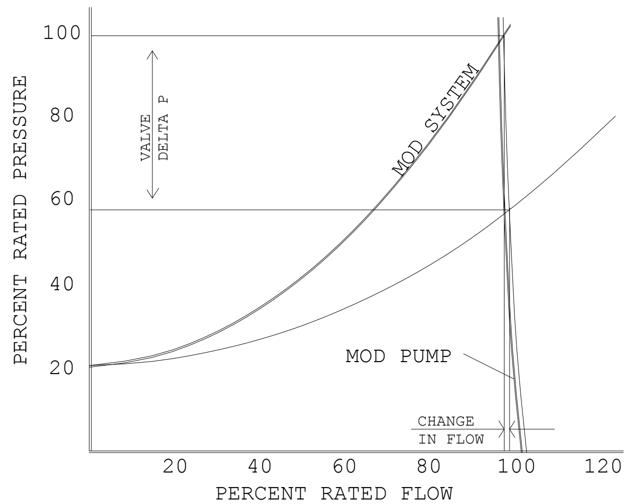

Fig. 2-3. Modified Curves: Discharge Throttling

SUCTION THROTTLING. Suction throttling has the same effect on the characteristic curve as discharge throttling and doesn't work either. PD pumps have a Net Positive Suction Head Required (NPSHR) just as centrifugal pumps do. In fact their requirements are even more stringent. Therefore restrictions and pressure drops in the suction lines must be similarly avoided.

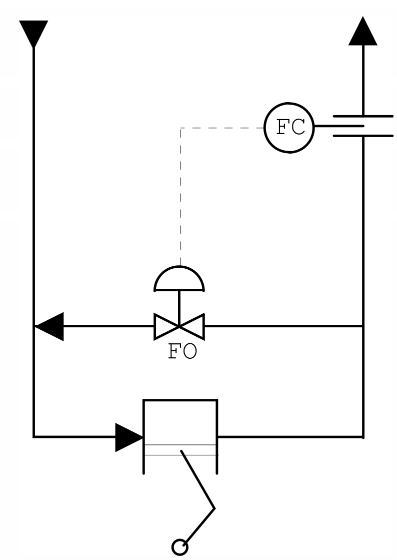

Fig. 2-4. Recycle Control

RECYCLE CONTROL. This leaves recycle control as the only means of using a valve to control a PD pump. The valve is installed in a line teeing off from the discharge and leading back to the source of the liquid, possibly a surge tank. It must be **fail open**, of course. Figure 2-5 shows its effects on the characteristic curves. Viewing the process from the point of view of the pump, its effect is to rotate the system curve clockwise around its intersection with the pressure axis. Note that the little "tail" at the bottom left of the modified system curve is due to the flow through the recycle valve before the discharge check valve has opened. The flow through the pump is essentially as before but the pressure to the process has been reduced. Process flow will, of course, also be reduced by the amount flowing through the recycle line.

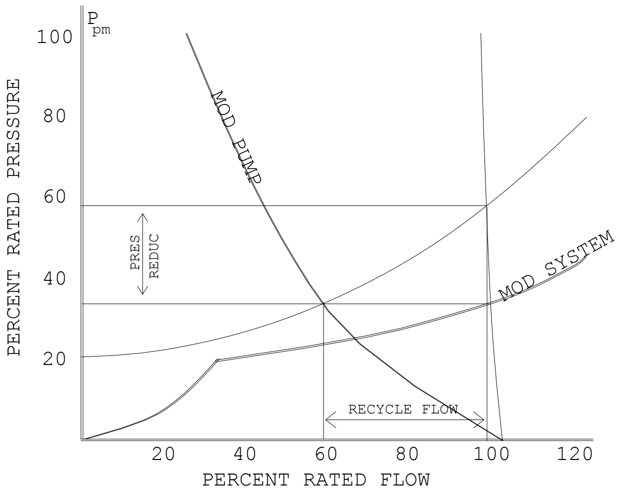

Fig. 2-5. Modified Curves: Recycle Control

Viewing the pump from the process gives a different perspective on the same phenomenon. This time it is the pump curve that is rotated counter clockwise around its intersection with the flow axis. This modified pump curve gives the effect of greatly increased internal leakage. From the point of view of the process, this is exactly what is happening. Note that I have not used the same operating points in Figure 2-3 as I did in Figure 2-5. It is simply impossible to show any significant reduction in flow on a curve representing the effects of discharge throttling.

Recycle control is an efficient method of control for PD pumps. Since the flow rate is essentially constant, the power requirement is roughly proportional to discharge pressure. Since the effect of recycle is to drop the discharge pressure, it results in significant reductions in power requirement. Nevertheless there is still wasted power in proportion to discharge pressure times recycle flow.

Recycle valves experience rather severe service if the pressure drop is high. Cavitation will destroy them if they are not appropriately selected. Two approaches exist to deal with this problem: The first solution is to drop the pressure in many small stages through the use of many twists and turns in the valve trim. The second is to tolerate the resulting cavitation by shooting the liquid as a jet through a small hole in the middle of a disk. The jet then blasts directly into the discharge piping. The line diameter is often increased immediately downstream of the valve and the wall thickness is also increased. In this way the jet cavitates down the middle of the pipe. It makes a terrific racket.

In either case it may be necessary to put a fixed restriction downstream of the valve. It should be sized so that the ratio of the high to intermediate pressure is the same as the ratio of intermediate to low pressure. Keep in mind that the restriction will reduce the rangeability of the valve by making it act like a quick opening valve. This is because the restriction becomes the dominant factor in the line once the valve is about half way open. From that point on, the valve has little control.

Recycle lines for PD pumps should be run back to the suction vessel. This allows any entrained bubbles to escape. If they do not, they can build up to the point where pump capacity is impaired. It may even vapour lock.

SPEED CONTROL. Speed control is an obvious method of controlling the flow rate of PD pumps since flow is essentially proportional to speed. Pressure can also be controlled by sliding up and down the system curve. Any point on the system curve can, in theory, be reached. Most drivers, however, have low speed limits which limit the turndown of the system.

Variable speed electric motors are somewhat modified versions of normal motors. They require special provision for cooling and lubrication at low speed. In addition, they require specialized electronic power supplies called "invertors". These units provide power of the appropriate frequency and voltage. They are, unfortunately, still quite expensive. A more simple type of electronic control is frequently used for small chemical injection pumps.

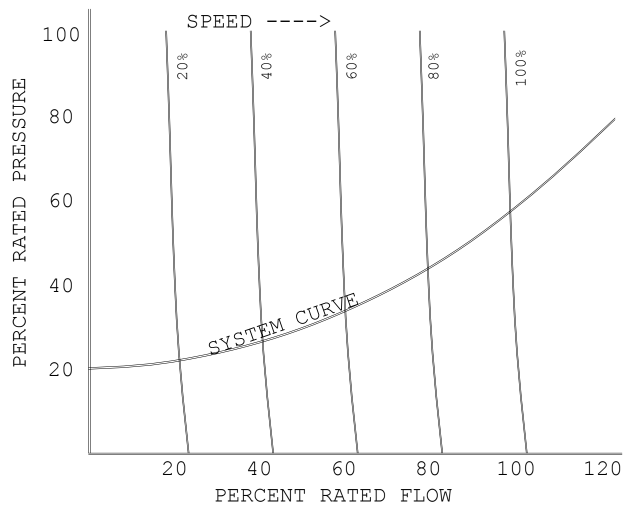

Fig. 2-6. Variable Speed

OTHER MEANS OF CONTROL. The great variety of types of PD pumps results in a variety of specialized means of flow control. A pneumatic actuator may be used to vary the geometry of the crank arrangement of a reciprocating pump so that each cycle displaces a greater or lesser amount of cylinder volume. Direct acting diaphragm pumps driven by compressed air or some other gas can be controlled by regulating the gas supply. There is also a technique known as "lost motion" whereby the crank arrangement first compresses a spring or volume pocket before it begins to work on the piston or diaphragm. These specialized methods are usually integral parts of the equipment and the controls engineer simply connects a pneumatic or milliamp signal to the appropriate input port. None of these methods changes the essentially constant flow nature of the pump curve. (The flow is still "constant" but at a different value.)

The efficiency of hydraulic or eddy current couplings is about the same as that of recycle control. This is because the torque on both sides of the coupling is proportional to ΔP. The power lost in the coupling will be proportional to torque times the reduction in speed. In other words, all unused power is being dumped. If the pressure does drop with a reduction in net discharge flow, then there will be a power savings. A valve is a cheaper way of accomplishing the same thing.

"Stroke Counting" is a method used when fixed amounts of liquid must be injected at specific intervals such as in batch processes. An electronic device is used to count the number of revolutions of a PD pump. After a sufficient number has been counted, the pump is shut off. When this method is used for pH control, the correct number of strokes can be calculated from a titration curve.

MEASUREMENT. The most common application for PD pumps is in high-pressure service. The flow rates vary from extremely small to moderately large. Pressure control is very common. Since the control valve tees off the discharge header, it is not significant where the sensing transmitter is placed. Keep in mind that the discharge will be pulsating. The pulsations may be relatively small for a rotary pump or they may be extremely large for a simplex (single cylinder) reciprocating pump. The degree of pulsation also depends on the effectiveness of the hydraulic pulsation dampeners that are often supplied with the pumps. If pressure or flow control is critical, the control systems engineer should encourage the biggest economical discharge dampeners. Small pulsation dampeners, called snubbers, should be installed on all instrumentation such as pressure gauges, switches and transmitters. This will extend their life as well as improve the signal. Many transmitters have built-in adjustable electronic damping. These should be adjusted so that the time constant is approximately twice the period of the expected pulses at the lowest speed. The phenomenon known as "aliasing" makes digital control systems such as a distributed control system (DCS) especially sensitive to pulsations. Aliasing can be best explained with the help of a diagram as shown in Figure 2-7. The rippling curve shows the actual flow rate of the discharge as it varies with time. The Xs show the points at which the DCS samples the measurement. The DCS gets the totally misleading impression that the system flow is slowly rising even if the average is quite constant. The usual reading the DCS gets is one of totally random fluctuations. Analog damping, either hydraulic or electronic, is absolutely essential for digital control. It prevents aliasing by filtering out high frequency components before they are sampled.

Flow control measurements have similar problems to pressure measurements. An additional problem arises in the case of an orifice plate or similar head type measuring system. Since the ΔP varies with the square of flow rate and it is the ΔP that is averaged, the resulting signal is not the average of the flow rate. Rather it is the square root of the average of the square of the flow rate. (Electrical engineers recognize this as the RMS -- root mean square.) As long as the shape of the pressure signal, over time, does not change, flow will be proportional to, but not equal to, root ΔP. The more cylinders in the pump, the smoother the waveform will be and the closer the measured to the actual reading. Discharge pulsation dampeners also help considerably. The measured flow on "ideal" (undamped, pure sinusoidal flow waveform) simplex and duplex pumps is 11% higher than the actual flow. An "ideal" triplex pump yields a measurement that is 1% high.

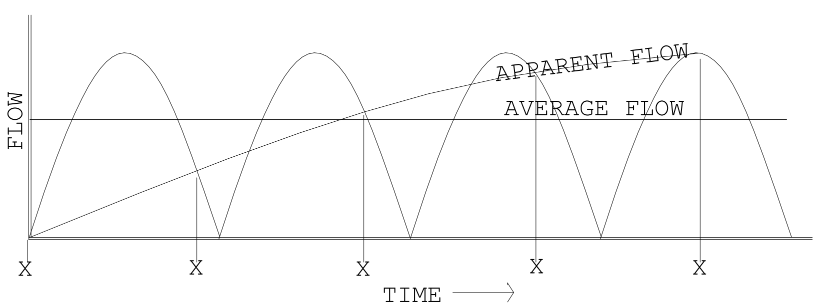

Fig. 2-7. Aliasing

Flow measurements on the discharge of high pressure pumps should be avoided. This may not be possible if the pump has a recycle loop that returns, as it should, to the suction vessel. In that case remember that the flow sensor will experience not only high pressure but also a high level of pulsation. Turbine meters are easily damaged. I am told that Coriolis flow meters do well in this service.

Certain classes of reciprocating pumps, known as metering pumps, have a very precise volume of liquid delivered with each stroke. The RPM of the pump can be used as an accurate flow measurement. However, individual calibration is required if this accuracy is to be realized. Note that even small amounts of entrained air or other bubbles can cause serious errors. Metering pumps are commonly applied for chemical injection. There is a simple way to calibrate them if extreme accuracy under varying conditions isn't an issue. A large glass cylinder is teed into the suction piping. If a valve between the cylinder and the supply is closed, the time it takes the pump to draw down the level by a fixed volume can be used to calculate a flow rate. The cylinder also serves as a level gauge to the supply tank. In some applications the fact that the pump is capable of developing high pressure isn't even an issue. It may be metering directly into an open tank or a low pressure line. In such cases the pump may need a back pressure valve on the discharge to ensure that the check valves seat properly. This item is usually supplied by the vendor as part of the pump package.

PD pumps are not generally used for level control in the process industries. The great variety of types of PD pumps inevitably provides exceptions to every generalization. The direct acting, pneumatically powered diaphragm pump is one of these exceptions. It is ideal for sumps containing sludges. The pump can be controlled by an entirely pneumatic control system thus eliminating all electrical connections. This has the added advantage of being absolutely safe in hazardous locations.

MACHINE PROTECTION. The greatest danger to positive displacement pumps is overpressure. The rigid, unyielding nature of the pump characteristic means that overpressure is certain if the discharge is blocked. Many smaller (non API) pumps[2, 3,4], such as the gear pumps used to supply lube oil for larger equipment, have integral relief valves to release pressure from the discharge back to the suction. In the majority of cases, an external relief valve must be supplied by the user. It must be connected as closely to the pump discharge as possible and must not have any means of blocking either its inlet or its outlet. It should discharge back to the pump supply. If, for any reason, the discharge is blocked and the relief valve is not capable of relieving, the pressure will rise very rapidly until something busts. It may be connecting rods, the check valves or even the cylinder head. Don't count on the motor stalling because events unfold very rapidly and the inertia of the system is sufficient to cause major damage. The most likely point of failure is the bolting on the discharge flanges.

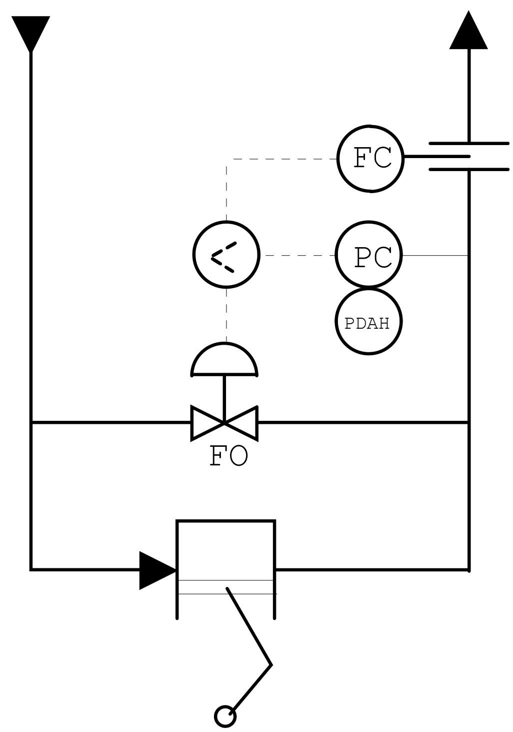

Fig. 2-8. Pressure Override

Direct acting pumps, such as those driven by compressed air, may not need a discharge relief if it can be shown the maximum pressure of the driving fluid is incapable of causing excess pressure.

It is often advisable to install a high discharge pressure shutdown switch or transmitter in addition to the relief valve. Good engineering practice dictates that operating controls be provided to avoid shutdowns or relief valve operation for normal operating situations. If it is possible for the pump discharge to be blocked under normal operating conditions, a pressure control loop must be provided on the discharge. This consists of a pressure transmitter, a controller and a recycle valve. If there is already a flow control loop on the discharge, a pressure override controller must be added. A common arrangement is shown in Figure 2-8. A deviation alarm on the pressure controller provides the pre-alarm for the high pressure shutdown. Whenever the pressure is above the setpoint of the controller, the alarm is on. This has the advantage of having only one setpoint for the two functions. Since the valve is fail open and the lower of the two signals drives the valve to the safe state, a low selector is chosen to pass the correct signal to the valve. Once again it must be stressed that overpressure conditions can arise extremely quickly. All components of the system must be selected with speed in mind. DCS controls with a scan rate slower than ½ second may be too slow. In any case, the valve may be too slow. Despite your best efforts it may be impossible to limit the pressure rise. In such cases it may be necessary to eliminate the high-pressure shutdown and to accept occasional relief valve action.

The suction side of the pump may also require protection. A relief valve is required unless all suction piping is rated for the full discharge pressure. Liquids, especially water, are quite incompressible. Even the smallest reverse leakage through a check valve can raise the pressure of a blocked suction sufficiently to rupture the line. This can happen even after the pump has been shut down! The discharge dampener will contain liquid at full pressure unless it has been relieved. The line rupture may occur minutes or even days after the pump has been shut down and isolated, depending on the relative sizes of the discharge and suction dampeners and the leakage rate. (Been there, seen it, don't want to see it again!)

A low-pressure shutdown switch or transmitter is required on the suction side of larger pumps. The NPSHR of reciprocating pumps is further complicated by what is termed the "acceleration head". (See the previous article in this series, **Controlling Centrifugal Pumps[1],** page 7, for a more detailed discussion of NPSHR and NPSHA. Note that there is one difference between NPSH for centrifugal and PD pumps: For a PD pump NPSH is specified in pressure units instead of elevation. This is because the operation of PD pump is not dependent on liquid density.) When the piston of a simplex pump begins its intake stroke, the liquid in the suction line is essentially stationary. The entire line contents must be accelerated rapidly to its maximum velocity, approximately three times the average velocity. There are two reasons for this three to one ratio: Firstly, the liquid isn't moving at all for half the cycle. Secondly, even when it is moving the velocity starts at zero and builds up to a maximum at mid stroke before reducing to zero again at the end of the stroke. The "suction" required to draw the liquid into the cylinder reduces the pressure sufficiently that air or vapour bubbles may develop. When these collapse during the discharge stroke, if not sooner, cavitation occurs. If the bubbles do not collapse, as in the case of air dissolved in water, serious hammering can occur in the cylinder. The air may accumulate to the point that the pump becomes vapour locked. Remember that air can compress into the internal clearances of the cylinder and then expand again on the intake stroke without ever being forced out of the discharge check valve. The low suction pressure shutdown device should be accompanied by some sort of pre-alarm. Acceleration head problems are greatly reduced for multi-cylinder pumps. Suction dampeners also contribute to making the flow rate more even.

Minor mechanical failure in PD pumps can cause significant vibration and subsequent serious damage to the entire machine. For this reason it is the rule to include a vibration switch on larger equipment. This switch need not be the extremely sensitive, multichannel system used on high-speed machinery. We are not monitoring the gradual deterioration of delicate bearings. What we are looking for is an abrupt event of considerable magnitude. Even the simplest switch will suffice. The usual type of switch is termed a "seismic" switch. It works by having a small weight held in place by a magnet against the force of a spring. A "bump" dislodges the weight from the magnet and allows it to open the shutdown contact. The usual means of "calibration" is a light whack with a hammer. A pre-alarm is not possible.

Larger PD pumps may have special lubricating requirements for the cylinders. The oil is supplied by small reciprocating injectors (miniature PD pumps) drawing from a small reservoir. The reservoir needs a low-level alarm which should also inhibit startup. A shutdown may not be necessary since damage from low oil level is not immediate. The reservoir is supplied from a larger lube oil tank through an integral float valve. The tank requires a low and a high level alarm. These can be provided by a single transmitter.

Variable speed pumps, especially those driven by engines, may require an overspeed trip. This should come from a separate sensor from the governor since it may be a governor failure that has caused the overspeed. A simple method is a small bolt mounted in a hole in the rim of the flywheel and held in place by a spring. Centrifugal force causes the bolt to project from the rim and trip a limit switch mounted on the frame.

SAFETY. There are no inherent dangers associated with PD pumps other than extremely high pressure or leakage of toxic or hazardous materials. Actually diaphragm pumps are especially suitable for toxic service since they have no rotating or sliding seals. The possibility of leakage or even rupture and a subsequent fire must be considered whenever flammable materials are being handled. Fire detection methods similar to those discussed in **Controlling Centrifugal Pumps[1],** may be necessary.

It is possible that a diaphragm may rupture during service. If the liquid is particularly hazardous, a double diaphragm may be used. In that case a tap will be provided by the manufacturer to install a pressure sensor for alarm or shutdown.

A fire safe block valve is needed on the suction whenever flammable liquids are being drawn from a reservoir with significant capacity[5]. Its interlocking must be handled slightly differently from that associated with a centrifugal pump. It is not advisable to slam shut the suction valve even if the pump is stopped simultaneously. Full vacuum may be induced during the rundown. If this causes air to be drawn into the piping an extremely hazardous situation is created. It is best to use a time delay circuit so that the suction valve is not closed until several seconds after the pump has been tripped.

It may also be desirable to have a fire safe block valve on the discharge. Since PD pumps are often in high-pressure service, there may be the potential of pressurized fluid forcing its way backward past the discharge check valve into a fire. Automatic closure should also be interlocked to occur at least several seconds after the pump has been turned off.

ACCESSORY INSTRUMENTS. Any instrument used to control the process or to provide some safety or machine protection function should, if possible, have a simple local device to verify its operation. In the case of PD pumps that means pressure gauges at both the suction and the discharge. Pressurized pulsation dampeners require pressure gauges to ensure that they are properly charged. Large reciprocating pumps have oil filled crankcases. A gauge glass (by vendor) and a thermometer should be provided.

The cylinder lube reservoir requires a sight glass. This is supplied by the vendor on API pumps[2, 3, 4]. The tank needs a level gauge glass whose span is broad enough to cover both alarm settings.

If the machine is equipped with cooling water jackets, there should be a thermometer on the outlet of every jacket. A single thermometer on the supply is a good idea. High outlet temperatures may not mean the pump is overheating!

The variety of PD pumps implies a variety of special requirements. Be sure to discuss these with the pump vendor to make certain that nothing "obvious" has been overlooked.

PARALLEL PUMP INSTALLATIONS. PD pumps are quite suitable for parallel operation. Since the discharge pressure of each pump rises as necessary, all pumps will discharge into the common header. A common recycle valve is sufficient for flow or pressure control.

Starting up a pump that is discharging into a header that is already pressurized by other pumps may overload its driver. To prevent this it is necessary to have an individual recycle valve on each pump. This may be a slow acting ball valve. Starting the pump then becomes a simple timed sequence in which the valve is first opened, then the pump is started, and finally the valve is slowly closed again. The pump should also be shut down in the same sequence. Remember that the ball valve will be opening against the full discharge head and may need a large actuator. In water service it is extremely important that the appropriate water resistant grease is used.

If variable speed pumps are used, the majority should be placed on fixed speed. One pump is then selected for process control to take the swings in demand.

SERIES PUMP INSTALLATIONS. PD pumps are not generally installed in series. Since series pumps must both discharge an identical flow and both are discharging a "constant" flow, it is extremely unlikely that the two can be matched without complex controls. It is common, however, to have one or more parallel centrifugal pumps servings as boosters to one or more parallel PD pumps. The centrifugal pumps serve to provide the NPSH that the PD pumps require. The PD pumps in turn can provide a very high discharge pressure.

The centrifugal boosters should have sufficient flow capacity to supply the pulsating requirements to the PD pumps. This means the full peak flow, not the average. If they need controls, they should be on pressure control by way of a recycle valve since there should be no interference in the suction to the PD pumps.

A warning: It may happen that the PD pump has a very low discharge pressure for some reason -- perhaps the piping has been removed for maintenance. It is then possible for the booster pump to push liquid through the various check valves and out the discharge without the PD pump being turned on at all. In fact, the flow may be even greater than if the PD pump were running!

SUMMARY. Figure 2-9 shows a typical arrangement for a positive displacement pump application. The following features are illustrated:

- Centrifugal booster pump with recycle pressure control and a minimum flow restriction orifice.
- Low suction pressure shutdown with alarm.
- Pressure gauge on the suction.
- High vibration shutdown and alarm on the crankcase.
- Thermometer and a sight glass in the crankcase.
- Discharge pressure controller with an alarm. The controller works through a recycle valve.
- Discharge pressure relief valve.
- High discharge pressure shutdown with an alarm.
- Discharge pressure gauge.

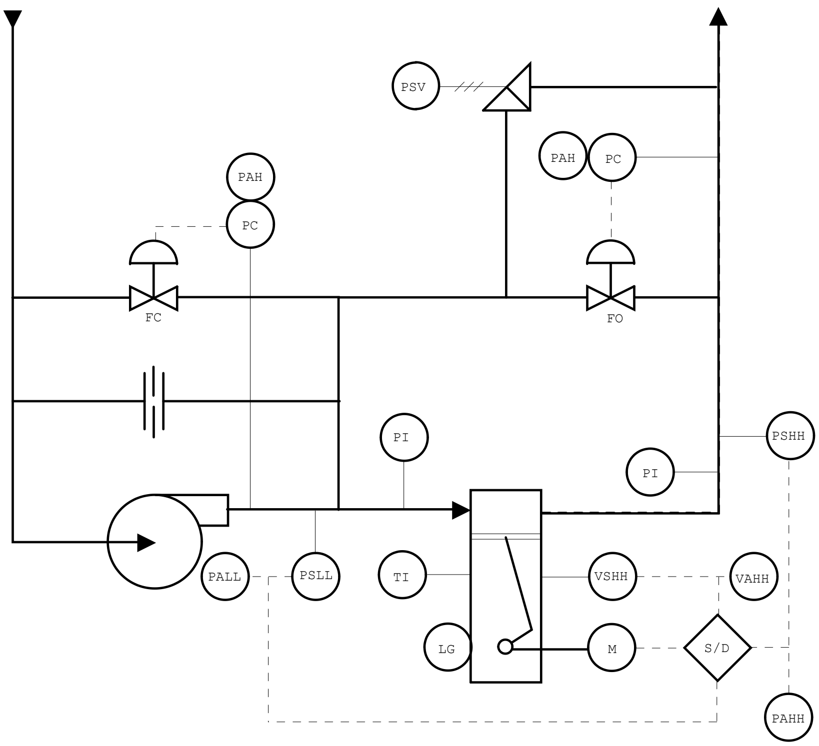

Fig. 2-9. A Complete System

A thermal relief valve must be around any isolation valve on the PD pump suction so that internal leakage does not over-pressure the piping.

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