SECTION 3.5

DISPLACEMENT PUMP FLOW CONTROL

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FLOW CONTROL IN INDIVIDUAL PUMPS

An inherent characteristic of positive displacement pumping of relatively incompressible liquids is that flow rate is proportional to displacement rate and independent of pressure levels. The capacity of a centrifugal pump operating at constant speed varies from a maximum flow at no developed pressure to zero flow at a definite limiting pressure known as shutoff head. The *average* capacity of positive displacement pumps at constant speed is, within design limits of pressure, practically constant, even though flow rate pulsations do occur as individual displacements are forced into the discharge pipe.

Flow control of positive displacement pumps is accomplished by

- Changing the displacement rate
- Changing the displacement volume
- Changing the proportion of the displacement delivered into the piping system

Throttle Control in Direct-Acting Steam Pumps Direct-acting pumps are controlled by speed change, which is effected by throttling the flow of steam (or other motive gas) to the drive cylinder. The magnitude of excess force on the drive piston over that required for the driven, or pumping, piston to force pumpage into the piping system dictates the stroke rate and therefore the capacity of the pump. A sensor that detects the desired result of pumping (pressure, level, flow rate, and so on) may be used to modulate the steam throttle valve.

Speed Control in Power-Driven Pumps Speed modulation is the most common means of flow control for power-driven pumps. The most rudimentary speed control is intermittent (start-stop) operation. The average capacity over relatively long time periods depends upon the percentage of time the pump operates at 100% versus the percentage of time it operates at zero flow. Of course, consideration must be given to the frequency of starts because electric motors may overheat if there is insufficient time for cooling after the inrush of starting current.

When continuous modulation of flow is desired, means of varying the driver speed or the ratio of speed reduction between the driver and pump are employed.

DRIVER SPEED CONTROL

1. Multispeed constant-torque motors offer limited steps in speeds.
2. Variable-frequency motor controls permit a wide range of fully modulated speeds but, at present, are limited in maximum horsepower (Subsection 6.2.2).
3. Direct current and wound rotor alternating current motors permit modulation of speeds within definite limits of torque capability (Subsection 6.2.2).
4. Gasoline and diesel engines provides speed variation capabilities within the limits where driver torque is adequate to satisfy the constant-torque requirements of the pump (Subsection 6.1.3).
5. Steam or gas turbines can operate over a limited speed range within their particular output torque limits (Subsections 6.1.2 and 6.1.5).

SPEED CHANGER CONTROL Because *most* positive displacement pumps operate at significantly lower speed than *most* drivers, a speed reduction unit is coupled between driver and pump. Capacity control by varying the ratio of the speed reduction is quite convenient. A number of methods are used.

1. *Variable-ratio belt drives* change the speed by changing the pitch diameter of driver and driven sheaves in response to capacity requirements (Subsection 6.2.5).
2. *Hydraulic torque converters* (hydrodynamic drives) vary the speed by regulating the *amount* of active drive fluid in the coupling. Because these converters relate torque to speed, they are sensitive to the driven torque requirement change that may derive from system pressure changes (Subsection 6.2.3).
3. *Hydroviscous drives* vary the slip between input and output shafts by adjusting the *distance* between elements in a viscous fluid environment (Subsection 6.2.3).
4. *Eddy-current couplings* also vary the slip between driver and driven elements but do so by varying the strength of a magnetic field (Subsection 6.2.1).

Variable Displacement Flow Control Rather than by speed control (changes in the number of displacements in a given period of time), flow may be varied by changing the *volume* displaced per stroke.

Variable strokes are generally limited to small metering or "controlled volume" pumps. Although large-capacity variable-stroke pumps have been built, the complexity of the mechanism involved and the development of other effective and economical means of flow control have precluded their use (Subsection 9.16).

Changing Delivery to the System Another means of capacity control is *not* to vary the pump capacity but to alter the amount of pumpage delivered to the system. There are two popular means of doing this.

SUCTION VALVE UNLOADING Suction valve unloaders cause the displacement to be ineffective during the strokes for which the unloaders are activated. They command either full or zero delivery while the pump is kept running. Thus, current inrush problems from frequent motor starts are avoided. Because discharge pressure is not developed when suction valves are unloaded, energy consumption is held to a minimum.

A pump valve is unloaded by mechanically preventing the valve plate from returning to its seat. If the suction valve is held away from its seat, liquid will ebb and flow through the valve from suction header to pump cylinder and from cylinder to header during the stroking of the plunger or piston.

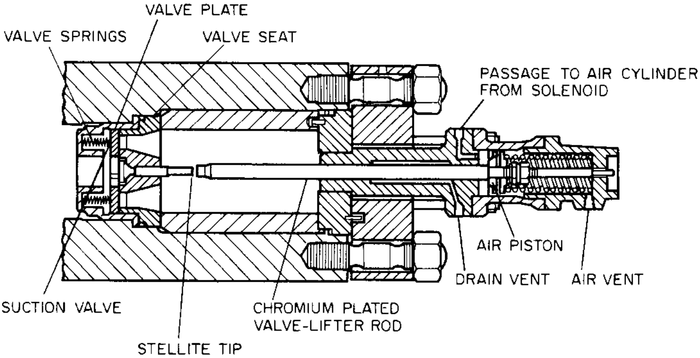

FIGURE 1 Synchronized unloading keeps the valve open through the use of a suction valve unloader.

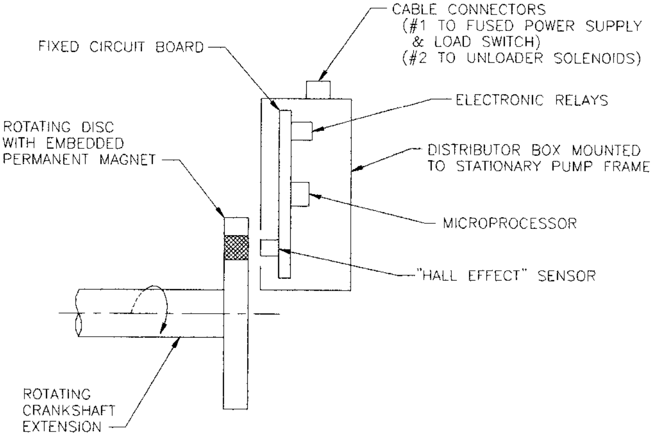

FIGURE 2 "Hall effect" microprocessor distributor system.

The unloader mechanism does not move the valve. The valve is lifted off its seat by the pressure differential created by normal pump operation. In synchronized unloading, the suction valve unloader (Figure 1) is retracted only when it is certain that the incoming flow will keep the valve open.

The unloader never resists pressure in the cylinder; it merely holds the valve plate against valve springs that had already been compressed and moves away from the valve while the springs are still compressed. This permits the valve to close when the plunger begins its discharge stroke.

For smooth transition between full flow and zero flow, the unloading and loading are accomplished in an immediate and identical sequence of the pumping order of the plungers. It is the function of the synchronized suction valve unloader distributor (Figure 2) to control unloading events in that proper and immediate sequence. Similarity can be drawn to the gasoline engine distributor in its function of assuring the proper and immediate sequence of firing of the spark plugs.

The distributor is driven directly by the crankshaft so its position is positively indexed to the stroking of the plungers. It provides an electrical signal to a solenoid valve, which admits motive fluid pressure to the unloader chamber when the suction valve to the particular cylinder has been opened. Then, in sequence, each of the remaining suction valves is retained so, in the first revolution of the pump after a control signals the distributor to initiate unloading, all suction valves are unloaded and the pump capacity is reduced to zero. When the control again signals for capacity, each suction valve is released, in sequence, during a single revolution of the crank.

While unloaded, the discharge valves do not function; they remain closed and serve as check valves against the pressurized discharge system. The suction valves remain open. Liquid enters from and is dispelled back into the suction manifold through the open suction valves. Therefore, no work is applied to the liquid, not even that required to open the suction and discharge valves. When the control calls for loading, the load is applied in steps equal to the number of plungers. Thus the pumping horsepower, as well as the liquid inertia in the pumping system, is changed in a number of steps equal to the number of plungers over the time span of one crank revolution.

The unloader consists of a spring-loaded pneumatic cylinder attached to the suction valve cover. The spring advances holding fingers that keep the valve away from its seat. Pneumatic pressure, applied through a solenoid valve in response to the distributor signal, creates a force on a piston that opposes the spring force and allows the suction valve to load (close). The system is normally arranged to fail in the unloaded position on either electrical or pneumatic pressure failure.

Distributor systems have evolved from a) direct mechanical linkages between reciprocating parts and the suction valves, to b) electromechanical interfacing, to c) electronic proximitor systems, to d) a "Hall effect" sensor signaling a microprocessor. The objective of each of these systems is to cause suction valve unloader solenoids to activate or de-activate in the appropriate sequence and at the appropriate position of the plunger during the suction stroke.

BYPASS CONTROL Ultimate delivery of pumpage to the system may be controlled by a discharge-to-suction bypass valve. Pump operation is continuous, with the possibility of modulating the flow to the system by regulating the portion "bypassed" to suction. A serious disadvantage is the full power utilization and full-load wear and tear even when at zero system capacity.

Evaluation of Flow Control Options Proper selection of the means of capacity control requires consideration of system control requirements and then evaluation of the options available to satisfy those requirements.

Precision, responsiveness, and degree of modulation required may limit options. First cost, maintenance requirements, and the effect on pump operating cost should then be weighed for viable options. To evaluate the effect of operating costs, it is necessary to determine (or reasonably assume) the expected pattern of operation throughout the capacity range. For example, if practically all operation except infrequent start-ups is to be at full pump capacity, little penalty should be assigned to the full power usage of a bypass valve or to the part-load losses inherent with hydroviscous or eddy-current drives.

If smooth modulation of flow is not essential, start-stop or suction valve unloading may be the preference. If smooth modulation *and* considerable operation at part capacity are necessary, variable-frequency motors or variable-pitch V-belt drives may be indicated.

Table 1 and Figure 3 provide some general guidelines. Each application should be evaluated on the merits of requirements and options.

FLOW CONTROL IN COMBINED DISPLACEMENT AND CENTRIFUGAL PUMPS

Systems that involve both centrifugal and reciprocating positive displacement pumps deserve some special consideration. Centrifugal pumps are often used as suction boosters to overcome acceleration head requirements peculiar to reciprocating pumps but are rarely used to supplement flow. Some unique characteristics of each type of pump that affect the other type must be considered in the design, operation, and control or the interrelated system.

TABLE 1 Comparison of several capacity control schemes for positive displacement pumps

Control Method	Degree of Modulation	First Cost	Operating Cost	Comments
		Directing-acting pumps		
Steam throttle	Full: zero to 100%	Low	Low	Steam pressure required to balance liquid piston force and overcome breakaway friction. Steam volume throttled to produce desired capacity.
		Power pumps		
Start-stop	Zero *or* 100%	Low	Low	Limited in frequency of starts because of temperature rise from inrush.
Multispeed motors	Steps dependent on motor winding	Medium	Low	Cost of motor controller switch gear motors must be assessed.
Variable frequency	Full: zero to 100% +	High	Low	Limited by current-handling capacity of solid-state controller.
Direct current	Full: zero to 100%	High	Medium	Drive is torque-speed sensitive, pump is torque-pressure sensitive at all speeds. Check drive for required torque at minimum and maximum speeds.
Wound rotor motors	Full: zero to 100%	High	Low	Drive is torque-speed sensitive. Pump is torque-pressure sensitive at all speeds. Check drive for required torque at minimum and maximum speeds.
Combustion engines	Variable for limited range	High	Low	Torsional analysis required to avoid high torsional stresses.
Steam or gas turbines	Variable for limited range	Medium	Medium	Drive is torque-speed sensitive. Pump is torque-pressure sensitive at all speeds. Check drive for required torque at minimum and maximum speeds.
Hydraulic torque converter	Full: zero to 100%	High	High	Low full speed efficiency.

TABLE 1 Comparison of several capacity control schemes for positive displacement pumps (*Continued*)

Control Method	Degree of Modulation	First Cost	Operating Cost	Comments
Power pumps				
Hydroviscous speed control	Full: zero to 100%	High	High at part load	Efficiency proportional to capacity. Loss to heat exchanger.
Fluid coupling	Full: zero to 100%	Medium	High	Full-speed slip loss greater than hydroviscous. Loss to heat exchanger.
Magnetic (eddy) coupling	Full: zero to 100%	High	High	Full-speed slip loss.
Suction valve unloaders	Zero *or* 100%	Low	Low	Synchronization with suction stroke avoids start-stop and shock problems.
Bypass valve	Limited	Low	High	Uses full power at zero capacity with full valve wear.
Variable-pitch belt	Limited	Low	Low	Limited to belt drive horsepower.

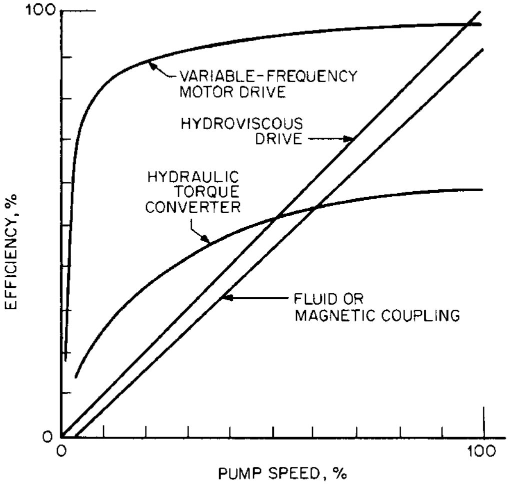

FIGURE 3 Relative efficiencies of speed control options.

Pertinent Positive Displacement Pump Characteristics

1. The discharge pressure produced is a function of the system requirement only and is independent of pump capacity.
2. The flow rate pulses between maximum and minimum values for each revolution of the crankshaft.

3. The pulsating flow imposes an acceleration head that adds to the net positive inlet pressure required (Section 3.1).
4. Being more energy-efficient, the positive displacement pump is normally the lead pump and the centrifugal pump is the supplement when operated in parallel.

Pertinent Centrifugal Pump Characteristics

1. The dynamic head (or pressure rise) produced is a function of pump capacity as well as of system requirements.
2. For satisfactory operation, the flow must be kept within a limited range of the best efficiency capacity (Subsection 2.3.1).
3. When used as a suction booster, the centrifugal pump must be designed so it cannot introduce air into the gas-intolerant reciprocating pump. (Gas in positive displacement pumps, like liquids in positive displacement compressors, may cause severe hydraulic and mechanical shock.)
4. Centrifugal pumps do not generate acceleration heads that impose on net positive suction head required. However, if a centrifugal pump is connected in parallel to a common suction line with a reciprocating pump, some of the system acceleration head loss from the positive displacement pump may affect the centrifugal pump.

Only two cases need to be considered: centrifugal pumps feeding (1) in series into reciprocating pumps to increase suction *NPSHA* to the reciprocating pump or (2) in parallel to augment the delivered capacity. It would be most unusual to encounter a positive displacement pump feeding into the suction of a centrifugal pump because of the high pressure that could be imposed on the centrifugal pump suction and because of the amplification of flow pulsations resulting from interaction of the characteristics of the two pumps, which could be deleterious to both pumps.

Series Operation, Suction Boost The flow rate is always determined by the positive displacement pump capacity and is independent of the centrifugal booster pump. The capacity is therefore controlled as with any positive displacement pump.

The purpose of the centrifugal pump is to supply sufficient pressure to satisfy the suction requirements of the positive displacement pump. The centrifugal pump must be sized to provide the maximum rate of flow of the positive displacement pump at a pressure high enough to meet the *NPSH* requirement of the latter.

With a flow-controlled positive displacement pump, speed control of the booster might be considered, as illustrated in Figure 4. The system pressure requirement can be satisfied by the positive displacement pump at all flow rates; therefore, total energy requirements may be reduced by using the less efficient centrifugal pump to develop no more than the required suction head.

If the centrifugal booster pump is run at constant speed, its share of the total head requirement will increase as system capacity is reduced.

Parallel Operation To increase the capacity of an existing pumping system, it is sometimes convenient to consider paralleling a positive displacement pump with a centrifugal pump. The interactions of the two pumps and the system must be considered and controlled for satisfactory operation.

Suction stabilizers and discharge dampeners, desirable for most reciprocating pump installations, become mandatory when a centrifugal pump and a positive displacement pump are connected in parallel. These devices are used to isolate, as much as possible, the effects of positive displacement pump flow pulsations from the sensitive centrifugal pump operating characteristics.

Centrifugal pumps in parallel with positive displacement pumps can supplement the system capacity only while they generate sufficient discharge pressure to satisfy the system requirement at the higher total flow. Undampened flow pulsations shift the centrifugal shutoff flow point relative to system flow at the frequency of the reciprocating

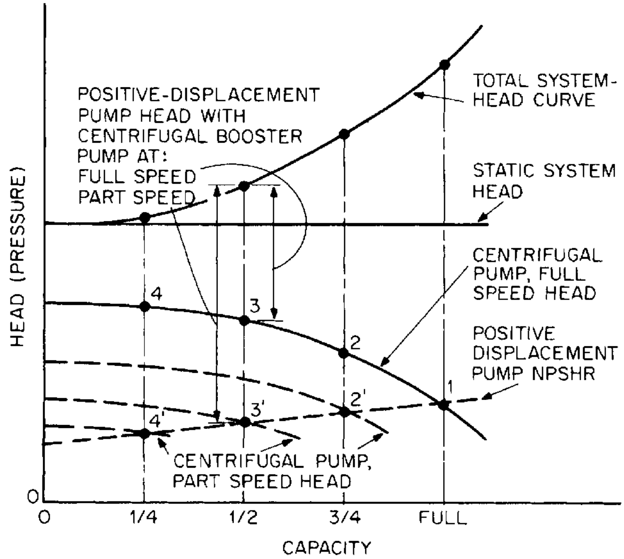

FIGURE 4 A centrifugal booster pump can satisfy the NPSH requirement of a positive displacement pump by operating either on its characteristic full speed curve 1-2-3-4 or with speed reduction along curve 1′-2′-3′-4′.

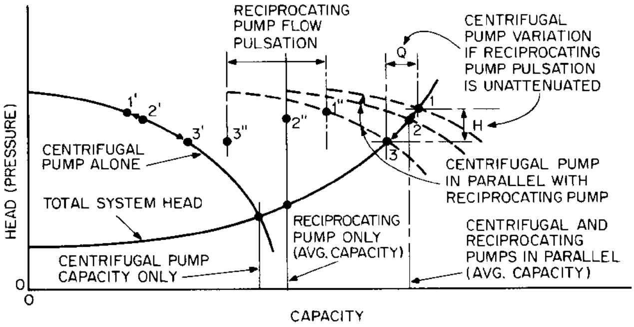

FIGURE 5 Parallel operation of undampened reciprocating and centrifugal pumps.

1. The reciprocating pump will operate at a capacity corresponding to its speed regardless of its discharge pressure.
2. If the system head is only static (constant head), the centrifugal pump capacity is constant and the system flow variation corresponds to the reciprocating pump variation.
3. If the system head is partially dynamic (as illustrated), the centrifugal pump will experience flow variations.
   a. The flatter the centrifugal pump curve, the greater the capacity and smaller the head variations on the centrifugal pomp.
   b. The flatter the system curve, the lower the capacity and greater the head variations on the centrifugal pump.

pulsation. From the system standpoint, the total flow varies along curve 1-2-3-2-1 in Figure 5. From the centrifugal pump standpoint, it varies along its characteristic curve, 1′-2′-3′-2′-1′. The reciprocating pump operates along curve 1″-2″-3″-2″-1″.

For purely static system-head curves, the centrifugal pump theoretically would not "sense" the pulsating flow. For dynamic system heads, the centrifugal pump flow varies contracyclically with the reciprocating pump pulsations. The magnitude of the centrifugal pump flow variation due to the positive displacement pump pulsations is a function of the system head curve, the centrifugal pump head-capacity curve, the degree of flow pulse imposed on the centrifugal pump discharge header, and the liquid bulk modulus (or compressibility).

FLOW CONTROL IN POSITIVE DISPLACEMENT PUMPS IN SERIES

Whenever positive displacement pumps are installed in series (such as for multiple-station pipeline service), some variable-capacity capability is mandatory. Otherwise, any variation in capacity between series pumps or series groups of pumps would result in disastrous interstation pressures.

The flow is determined by the first pump in the line. Subsequent pumps should be equipped with capacity controls responsive to their inlet pressures. The preferred control is a continuous-modulation type, such as variable speed, unless large reservoir capacity is available between pumps.

Recirculation from discharge to suction through a throttling bypass valve may be used, at the expense of energy, to match the delivery from downstream pumps to upstream pumps. Excessive bypass flow in relation to through flow can result in significant temperature rise of the liquid.

When downstream pump capacity is less than the upstream delivery, the interpump pressure will rise, indicating a need for increased capacity. When the downstream pump capacity exceeds the upstream delivery, the downstream pump will "draw down" the interpump pressure to the point where net positive inlet pressure difficulties are ensured.

Reservoir accumulators between pumps permit a limited degree of mismatch in capacities, allowing the use of incremental capacity controls, such as suction valve unloading and intermittent pump bypass.

In any event, effective discharge dampeners on the upstream pump and suction stabilizers on the downstream pump are necessary to prevent the inherent pressure pulsations and control modulation variances from adversely affecting operation.

FLOW CONTROL IN POSITIVE DISPLACEMENT PUMPS IN PARALLEL

Because the capacity of positive displacement pumps is virtually independent of head, there is no problem from the head-capacity characteristics in parallel operation—even for pumps of different sizes.

Particular attention to suction acceleration head requirements is necessary when more than one pump is taking suction from a common suction pipe. Because it cannot be assured that two pumps will not, at some point, have simultaneous suction strokes, the acceleration head requirements of each pump must be added for that portion of the suction line that furnishes the total flow. This suggests extra large suction lines, individual ones from the liquid source, or suction stabilizers sized for the total flow with individual outlet connections for each pump.