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PUMP CONTROLS AND VALVES

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CONTROLS

Pump control in the broadest sense gives the pump user (1) the flow rate, pressure or liquid level desired, (2) protection for the pump and system against damage from the pumped liquid, and (3) administrative freedom in decisions on operations and maintenance.

Control System Types Pump control systems range in complexity from single hand-operated valves to highly advanced, automatic flow control or pump speed control systems. Pump type and drive type are factors in control system choice. For centrifugal pumps, either change of speed or change of valve setting can control the desired variable. For positive displacement pumps, whether reciprocating, rotary, screw, or other type, control is by change in speed, change in setting of bypass valve, or change in displacement. The last-mentioned method is found in metering and hydraulic drive pumps. Although this chapter considers only control systems having valves as final control elements, the sensing elements discussed also serve in pump speed control systems.

Pump control systems divide readily into two types: on-off and modulating. The on-off system provides only two conditions: a given flow (or pressure) value or a zero value. A valve is therefore either open or closed, and a pump driver is running or not. The modulating system, on the other hand, adjusts valve setting or speed to the needs of the moment. Either type of system can be automatic or manual.

System Essentials All control systems have

1. A sensing or measuring element
2. A means of comparing the measured value with a desired value
3. A final control element (a valve) to produce the needed change in the measured variable
4. An actuator to move the final control element to its desired position
5. Relaying or force-building means to enable a weak sensing signal to release enough force to power the actuator

The sensing or measuring element is often physically separated from the comparison and relaying means, which are usually housed together and called the *controller*. The actuator and valve are physically connected and may be at a distance from the controller.

In a very simple control action, such as one based on an administrative decision to shut down temporarily one of several small parallel pumps in service, some of the five essentials may be supplied by the operator who turns the valve handwheels and pushes the motor stop button. Nevertheless, the essentials must always be present in some form.

EFFECT OF RATE OF CHANGE The nature of the rate of change of the measured variable or desired value with time gives a convenient guideline in pump control. The chief types of change are

1. Slow change (practically steady state)
2. Sudden change from one steady state to another (either a nearly instantaneous step change or a high-rate ramp change)
3. Fluctuation at varying rates and in varying amounts

Slow change involves questions of the ability of the control system to hold the desired value accurately and not lag unnecessarily during the change. Equal accuracy when approaching the new value from above or below is also desired.

Sudden change involves additional questions of whether the system will be excited into amplification of some types of fluctuations and go totally out of control. Systems involving fluctuation changes are the most difficult to design and operate; such factors as the inertia of the control elements, amount of liquid in the system, and dynamic behavior of each element and of the elements together must be considered.

OPEN-LOOP CONTROL The simplest mode of automatic control is open-loop control, in which the pump speed (or displacement in some pump types) or the control valve setting is adjusted to and held at a desired value calculated or calibrated to produce the required output of flow, level, or pressure. The calculation can result in a cam for the controller or positioner or a particular characterization of a valve plug. In operation, only the deviation of the input variable from its desired value is measured and the control system adjusts the input variable to eliminate the deviation. Because the output variable is not measured, a change in the conditions on which calculation or calibration was based will introduce output errors. Change of input variable can be done manually or by another control system. For example, a pump may be speeded up by a rheostat, or the air pressure to a valve actuator may be changed by changing a pneumatic pressure control valve setting. Open-loop systems are also called feedforward systems, in contrast to feedback, or closed-loop systems. Open-loop systems are stable, simple, and quick in response, but they tend to err as downstream conditions change.

CLOSED-LOOP CONTROL A closed-loop control system eliminates much of the error of the open-loop system. In the basic closed-loop, or feedback, system, the output variable is measured and the value compared with an arbitrary desired or set value. If the comparison reveals an error, the pump speed or control valve setting is changed to correct the error. Large-capacity water tanks or lag in the control system can introduce delays in establishment of the new output value, and the system can therefore overcorrect and oscillate back and forth unless design prevents this.

ON-OFF CONTROL The simplest closed-loop systems operate on-off between fixed limits, such as water level or pressure. The on-off action is at the extremes of a wide or narrow band that can be set at any point in the range. For example, a tank level control may work in an on-off band of 1 in (2.54 cm) or 10 in (25.4 cm) at any level in a tank that is 5 ft (1.5 m) deep.

PROPORTIONAL CONTROL This is the basic type of closed-loop control. Within a wide or narrow band of output variable values, the controller input, such as actuator air pressure, is proportional to the deviation from the set point, or desired value, at the band center. If the band is very narrow, for example, 1 in (2.54 cm) of level in a 60-in (1.5-m) tank, the controller will apply full air pressure to the valve actuator at a $\frac{1}{2}$-in (1.27-cm) deviation from the set level in one direction and minimum air pressure at a $\frac{1}{2}$-in (1.27-cm) deviation in the other direction. This is close to the effect of an on-off control. If the band is wider, say 20 in (50.8 cm) of level in the 60-in (1.5-m) tank, the air pressure will vary from minimum to full pressure over the 20-in (50.8-cm) band and the system will be less sensitive and apply less correction for a given small change in output variable. The lower sensitivity can make the system less likely to overshoot or hunt. Because a given controller output corresponds to every value of deviation from the set point, the simple proportional system will not come back to its set point if the output variable changes as a result of changed demand, such as for more water from the tank. The difference between set point and actual new equilibrium value of level is called *offset.* Narrowing the band will reduce the offset but may cause intolerable oscillations or hunting.

To improve response and stability and to achieve very high accuracy, however, several refinements may be needed. Addition of reset to a simple proportional controller will eliminate offset. This is the proportional-plus-reset or proportional-plus-integral system. In terms of the proportional band, reset means that the band is shifted in such a way as to produce slightly more correction and return the output variable back to what is desired. The reset feature may impair stability, however, because of the added control action.

Derivative action is an added refinement to improve stability and response. In this, the rate of change of the measured output variable is what determines the controller output. A step or sudden change in measured output variable will cause a momentary large increase in controller output that will initiate response. When the derivative action fades, the basic proportional-plus-reset action takes over to restore conditions.

The open-loop system, sensing a change in input variable and therefore giving rapid response, is exploited by adding it to the closed-loop system. An example of a feedforward-feedback system in pump flow control is the three-element boiler feedwater regulator.

Sensing and Measuring Elements In automatic control of a pump, these elements detect values of and changes in liquid level, pressure, flow rate, chemical concentration, and temperature. The signal emitted by the element often needs amplification or conversion to another medium, which is done in a transducer. Air pressure to electric voltage or current and rotary motion to electric voltage are common transformations.

LIQUID-LEVEL SENSORS The simplest of several types of sensors is the float in the main tank (or boiler drum) or in a separate float chamber connected at top and bottom to the tank or drum (Figure 1). The float can be a pivoted type, with motion transmitted outside the chamber by a small-diameter rotating shaft or translational rod attached to the lever arm near its pivot to obtain mechanical advantage. A rod of the latter type can actuate the stem of a balanced valve to control liquid flow and thus liquid level in the supplied tank.

Floats on vertical rods can actuate switches outside and above the float chamber (Figure 2). Depths can vary from less than 1 to more than 50 ft (0.3 to 15 m), with rod guides often necessary at the greater depths. In some cases, the floats slide on the vertical rod between adjustable stops. The floats then push upward or downward on the rod at the desired control levels and trip the switch above. In a displacer-type arrangement for open tanks, a ceramic displacer is suspended from one end of a stainless steel tape that passes over a pulley and down again to a counterweight. The counterweight compensates for part of the ceramic displacer weight, so it floats in the liquid. The extended pulley shaft drives through a reducing gear to a shaft that carries mercury switches controlling as many as four circuits (Figure 3). The gearing allows the displacer to travel as far as 30 ft (9 m), with level adjustment between 2 and 27 ft (0.6 to 8 m). A weighted overcenter mechanism in the switches gives quick make and break.

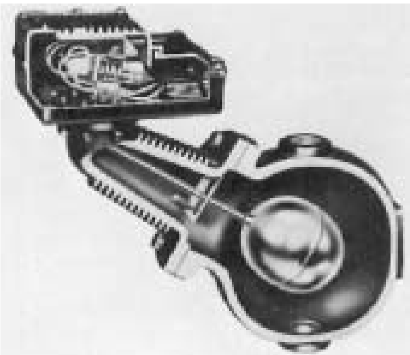

FIGURE 1 Low-water cutoff and alarm are purposes of this liquid level sensor (McDonnell & Miller).

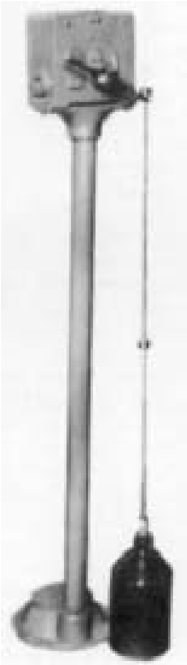

FIGURE 2 Adjustable tops on rod actuate lever arm to tilt mercury switches as float moves (Autocon Industries)

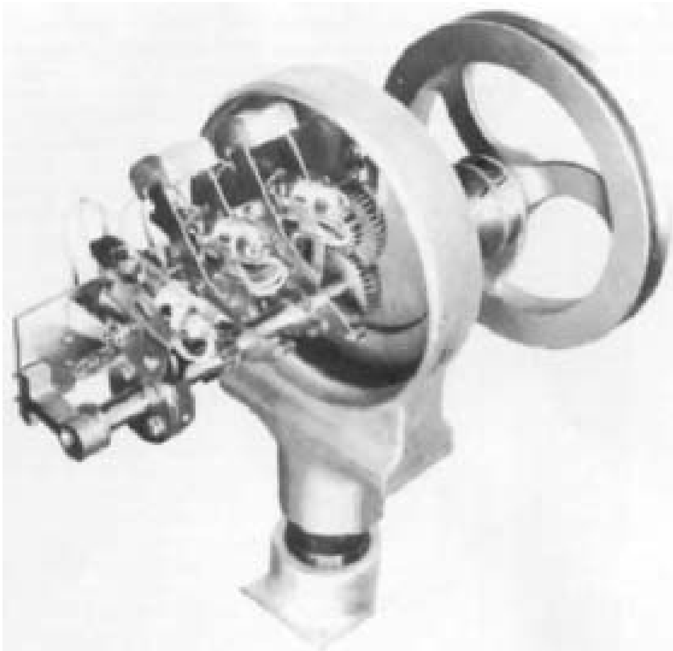

FIGURE 3 Mercury switches in liquid level sensor head are tripped by adjustable cams (Autocon Industries).

In other applications of the displacer, porcelain bodies on a cable are suspended from the armature of a magnetic head control. In one form, a spring partly supports the weight of the displacers. As liquid rises to the displacers in succession, their apparent weight decreases and the spring can move the cable and armature upward to actuate snap-action switches. The displacers can be moved up and down the cable to initiate action at the desired levels. Three displacers can be mounted on a cable for such applications as one pump actuated by the center displacer, a second pump by either the top or bottom displacer, and an alarm by the third displacer. Displacers are advantageous for dirty or viscous liquids that are still. Levels covered are from 1 to more than 10 ft (0.3 to 3 m).

The pulley shaft of the tape suspended displacer can also drive a potentiometer. The potentiometer output can be applied to solid-state control equipment handling recording, pump start and stop, and alarms.

The connection between float and switch need not be mechanical. An armature can be attached to the top of the float rod sliding in a tube. Outside the nonmagnetic tube is mounted the control switch, with a permanent magnet attached to it and set close to the tube. When the level rises, the armature passes the permanent magnet and attracts it, so the switch is actuated. A spring retracts the magnet when the level falls enough, and the switch is reactuated. A float arrangement of this kind, although limited in range, finds use as a low-water cutoff for boilers to 600 lb/in^2 (40 bar*) gage pressure. Switches are dry-contact or mercury type. Two of these units can be placed at different levels to give both high- and low-limit control.

Liquid level control systems without floats operate on several principles. If the liquid is at all conductive, probes can be used. The electrode probes are fixed, usually mounted in the same holder, and extend down into the tank (Figure 4). Two or three electrodes are

*1 bar = 10^5 Pa.

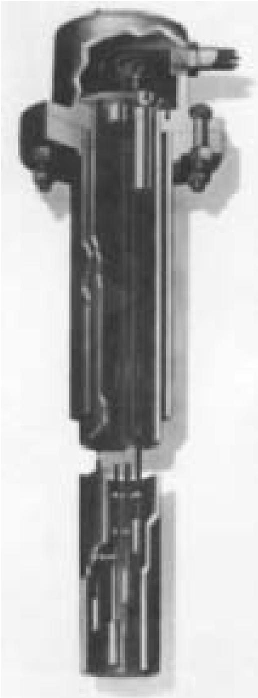

FIGURE 4 Electrodes suspended on cables sense tank water level below ice (B/W Controls).

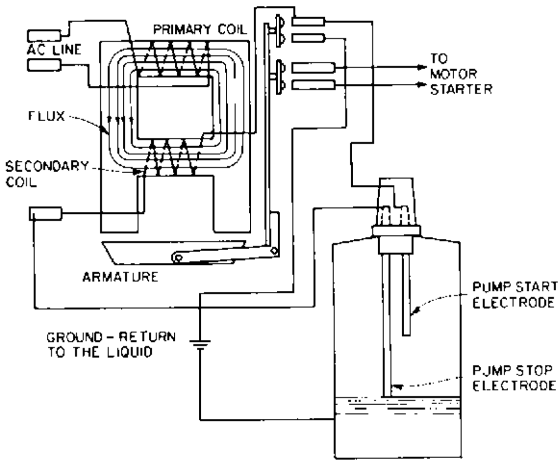

FIGURE 5 Induction relay: when liquid reaches pump start electrode, current flows in secondary coil and diverts flux to lift armature and close motor contacts (B/W Controls).

most common. Inductive or electronic relays are also part of the control system and actuate pumps or valves.

In a tank filled by a pump, a drop-in level below the lower electrode breaks the circuit to allow a relay to start a pump or open a valve. When the liquid rises to the high-level electrode, the direct electric circuit between electrodes is established and a relay stops the pump or closes the valve. In an induction relay (Figure 5), the line voltage is separated from the control circuit by a primary and secondary coil arrangement. The relay depends on the specific resistance of the liquid, which can vary from that of metallic circuits to that of demineralized water. Electronic relays have low potential and low electrode current.

Fixed probes usually do not exceed 6 ft (1.8 m) in length, but suspension electrodes are available for deeper tanks or higher level differences. Pressure-tight electrode holders capable of operating at 10,000 lb/in^2 (690 bar) are available. Temperatures are generally limited to 450°F (232°C). For tanks where icing is a problem, a pipe sleeve in which the probes are suspended can be supplied (Figure 4). An immersion heater near the sleeve bottom warms the water when the pump is not in operation.

Bubble sensors measure liquid level by determining the air pressure required to force a small stream of air bubbles through the lower end of a tube extending to the bottom of an open tank. The air flow tends to keep the tube and tube end clear in liquids that contain solids. Floats and probes are eliminated in this method, and only the air flow regulator and pressure switch are exposed to corrosive effects. The air stream flow rate can vary over a range without affecting air pressure. The specific gravity of the liquid must be known to allow the instrument to be calibrated. Because the measured variable is air pressure, the other instrumentation can be set at distances of 250 ft (76 m) horizontally or vertically. The range of liquid level is 6 in (15.2 cm) to about 32 ft (9.8 m). Sewage, industrial processes, and water supply are some applications.

Notwithstanding the low air pressure involved, the differential sensitivity of pressure switches for bubbler sensors is about 0.5% of maximum operating range. Air consumption is about $1\frac{1}{2}$ ft^3/hr (0.042 m^3/h) when the air flow regulator is set for 60 to 80 bubbles/min. The effects of air pressure failure can be prevented by providing a cylinder of carbon dioxide gas; a pressure switch and solenoid valve will introduce the gas to the system if the compressor fails.

PRESSURE SENSORS Pressure controllers of the simple on-off variety may have a single-pole double-throw mercury switch actuated by a bourdon tube. A typical differential value is 2% of maximum scale reading. Adjustment to desired cutin (low) pressure is made by a knob on the case. Pressure ratings go to 5000 lb/in^2 (345 bar) for these devices. Proportional control can be added to controllers of this type by incorporating a slidewire potentiometer (Figure 6).

In other types of pressure sensors, one sensor is provided for pump start and one for pump stop. Adjustable time delay prevents surging or waterhammer from giving a spurious start or stop signal. Increasing liquid pressure transmitted through tubing to an air chamber acts on a bellows and, overcoming adjustable spring tension, trips a mercury switch. The differential sensitivity of the bellows-type sensors is 0.5% of maximum operating range. Maximum pressure is about 175 lb/in^2 (12 bar) gage because the systems are intended for use on open tanks. Sensors, timers, and relays can be mounted in a cabinet located near the tank or even near the pump.

Air trapped in a bell and pressurized by rising water is the actuating mechanism for another alarm switch (Figures 7 and 8). A synthetic rubber diaphragm in the switch body mounted above the bell and connected to it by a small pipe is caused to tilt a mercury switch and thus give the alarm. A rise in level of about $1\frac{1}{4}$ in (3.2 cm) above the bell mouth will activate the switch.

ALTERNATORS An alternator may be installed to achieve regular use and equal wear of each pump in multipump installations. The simplest versions serve on two-pump systems, but more advanced designs can rotate starting sequences of as many as 12 pumps. In one version of the two-pump alternator, a solenoid plunger picks up and causes a four-pole double-throw switch to take alternate positions, maintaining a position after the solenoid is de-energized. If one pump leads with the other coming into service only to augment it, the switching compensates accordingly.

If starting sequence is to be rotated for more than two pumps, a motor-driven rotor can be advanced a given number of degrees each time a pump motor operates. The rotor contacts are connected together in pairs to provide circuits between pairs of stator contacts. Other control variations available in this regard are a change in sequence after a timed interval and an option of starting the pump that has been idle longest and stopping the pump that has run longest. Although many alternators operate on the same voltage as the loads, variants are available for operation from the low voltage and current ratings of control equipment.

TRANSDUCERS AND TRANSMITTERS The variable that is most convenient or advantageous to measure is rarely the one best suited for direct use in the control system or for actuation of the final control element. A small differential pressure in a liquid level or flow control system can scarcely open a large valve. Conversion of measured variable values to another signal medium is therefore necessary and is the task of transducers and transmitters. These two terms are used interchangeably to some extent, although the transducer usually converts a signal to an electric current and the output of the transmitter is usually an air pressure.

A pressure-to-voltage transducer is especially useful in pump control. In one design, a bellows subjected to the pressure of the liquid transmits force to a pivoted beam that

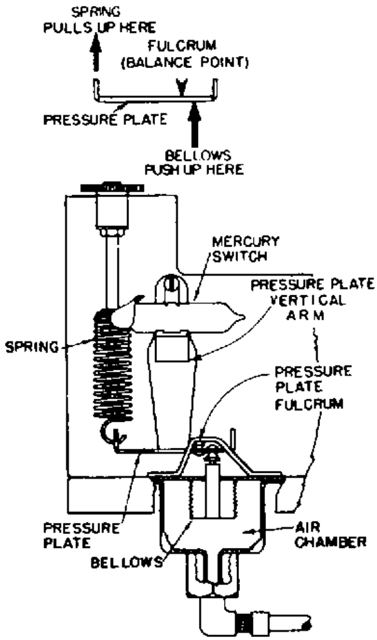

FIGURE 6 Pressure trip point is adjustable in this pressure switch (Autocon Industries).

FIGURE 7 Alarm for level rise has bell connected to switch mechanism by 1-ft (0.3-m) pipe (Autocon Industries).

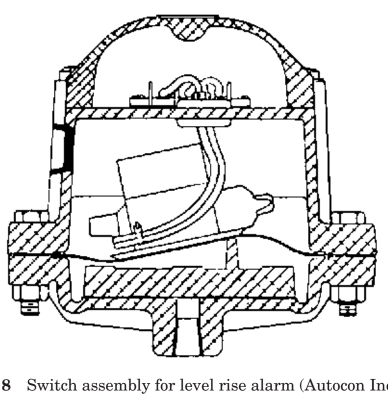

FIGURE 8 Switch assembly for level rise alarm (Autocon Industries)

moves a core in a differential transformer or motion transducer to produce a 3- to 5-V output. The beam is balanced by a spring, and another spring allows the minimum pressure for voltage output to be set, which is equivalent to zero suppression. Zero suppression here can go as high as 95%.

Differential pressure transducers may operate on a force balance principle with a very small motion of the bellows. The motion is converted to rotary motion in a ram or shaft, which then moves a differential transformer core to give an output signal that can vary from −2.5 to +2.5 V dc.

A transmitter is a device that can sense pressure, temperature, flow, liquid level, or differential pressure and convert the signal to a pneumatic pressure for transmission to receiving instruments several hundred feet distant. The pressure-sensing transmitter can span ranges to 80,000 lb/in^2 (5500 bar). The differential pressure type allows low differences in air or liquid pressures, such as a flow orifice develops, to be amplified through linkage and force balance mechanisms. An air pressure of 3 to 15 lb/in^2 (0.2 to 1 bar) in the air line from the transmitter is the result. Differential pressure transmitter designs are available to withstand primary system pressures to 6000 lb/in^2 gage (400 bar), whereas the differential pressures span ranges between 5 to 25 and 200 to 850 in (13 to 64 and 508 to 2160 cm) water.

TELEMETRY SYSTEMS When pump control must be exercised over distances greater than the few hundred feet over which most pneumatic control equipment can operate, telemetry systems find application. In some of these systems, the sensor's output is converted to a proportionally variable 3- to 15-V dc voltage at the transmitter input. The transmitter then converts the dc voltage to a square-wave pulse with duration varying in proportion to the input signal. The resultant pulse width modulation (PWM) signal is sent directly over transmission lines or via tone carrier in microwave, VHF, or UHF systems. Transmitting the bipolar PWM signal alone requires direct wiring with less than 500 ohms resistance. This means as much as 24 miles (37 km) on direct telephone lines. The PWM signal eliminates loss of information from signal amplitude variations, and the bipolarity of pulses reduces line capacitance effects.

With tone transmission, either amplitude modulation or frequency shift is used.

The receiver converts the pulse signal back to a variable 3- to 15-V dc signal identical to the transmitter input signal and capable of use for indication or control. If transmission is not received for a certain time period, an alarm can be actuated and the pumps started or stopped.

Constant Speed Control Where pump speed control is economically justified, it is a preferred method of obtaining the desired output parameter, such as flow rate, head, or liquid level. If the pump operates at constant speed, there are four common control means:

1. On-off
2. Throttling by valve
3. Bypass by valve
4. Submergence

The on-off method with a single pump largely focuses on liquid level or temperature range control. Centrifugal and positive displacement pumps can be controlled by this method. If an accumulator is installed downstream, the method can be extended to head control. With multiple pumps in parallel, flexibility is slightly greater and a coarse control over flow rate is possible.

The simplest mechanism for on-off control of constant-speed pumps is the push button switch and starter for across-the-line start of small pumps. For large pumps, reduced-voltage starting is customary. Number of starts per hour is restricted in all cases to prevent overheating. The electric impulse to start or stop the motor can originate in any of the sensors or switches described above.

Throttling by valve is very common and can provide refined control under difficult conditions where rapid response and outstanding dynamic stability are sought, as in boiler feedwater control. Positive displacement pumps cannot use this method.

Bypass by valve is an occasional variation of valve control based on the bleedoff of discharge liquid to reduce the flow rate at a downstream point or to allow a cooling flow to pass through a constant-speed pump when its discharge has been blocked. The method can serve both centrifugal and positive displacement pumps.

Submergence control, for centrifugal pumps, relies on a temporary decrease in available *NPSH* to reduce the pump flow rate to the value at which liquid is entering the sump

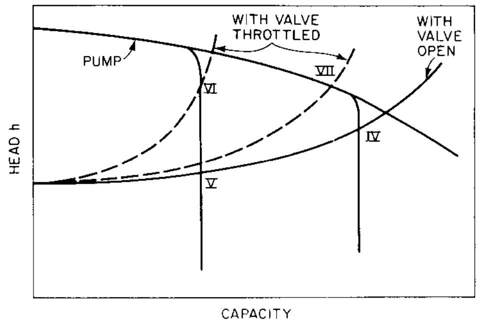

FIGURE 9 In submergence control, operation can be at points where restricted-capacity curve intersects piping characteristic (IV, V, VI) or on regular pump characteristic (VII).

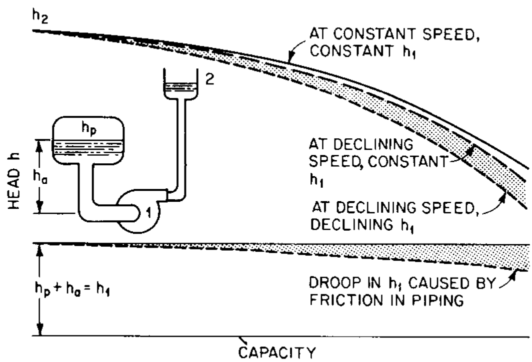

FIGURE 10 The centrifugal pump characteristics changes depending on speed and head at inlet.

(Figure 9). The method services for condensate, and design precautions prevent rapid cavitation damage.

VALVE-THROTTLING CONTROL The chief elements of centrifugal pump performance are shown in Figure 10. At any given flow rate (capacity), a centrifugal pump produces a discharge head consisting of the static head on the pump inlet and the dynamic head imparted by the pump. At higher flow rates, speed usually declines slightly, lowering the characteristic curve as shown. In addition, the higher flow rates produce more frictional head loss in the inlet piping so the pump senses an inlet head slightly less than the static head developed by the weight of the liquid column and the effect of compressed gas or upstream pumps.

The pump can deliver any flow rate along the curve. What determines the actual flow rate at any instant is the characteristic curve of the downstream piping (system curve), as shown in Figure11. Under zero-flow conditions, there is a gravity head of liquid and perhaps a pressure in a container, such as a boiler drum. When liquid flows, piping friction head is added. Piping friction causes the system curve to turn upward, roughly parabolically. If a downstream control valve, previously wide open, is throttled, a new and more rapidly rising system curve is established. The intersection of a pump curve and system curve plotted on a single chart (Figure 12) indicates conditions at the pump discharge. The combined plot also shows that the flow rate or discharge head will be modified by a change in other parameters besides throttle valve setting. For example, an increase in pump speed

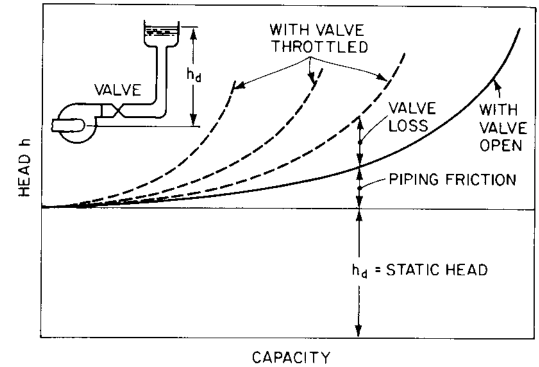

FIGURE 11 Static head, piping friction, and valve loss determine the piping characteristic downstream of pump.

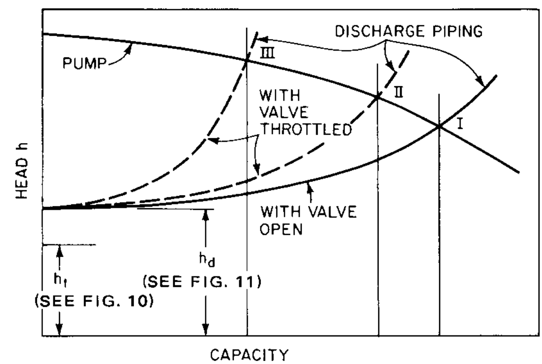

FIGURE 12 Intersection of combined pump and piping characteristics is operating point (I, II, III).

will lift the entire pump curve up and move the intersection point to higher flow rate and head. Decreased pressure in a boiler drum will lower the entire system curve and move the intersection point to higher flow rate and lower head. Throttling the inlet line to the pump will reduce the inlet head and cause the pump curve to start at the same point, but slope downward at a faster rate. The pump curve will then intersect the unchanged (downstream) system curve at lower head and flow rate.

BOILER FEEDWATER CONTROL In its original and simplest form, this control maintained the water level in a boiler drum (Figure 13). Although this is still the primary objective in many boilers, in other applications, a balance of steam flow rate against feedwater flow rate is the primary objective, with level maintenance a secondary factor unless it exceeds preset limits. In steam generators operating above the critical pressure of 3206 lb/in^2 (221 bar) abs, the feedwater turns to steam without a water level being visible, so temperature and flow rates are the variables to be controlled.

Both on-off and modulating control are used in feedwater control systems. One classification of boiler feedwater control systems is based on whether the system is electric or pneumatic. Another classification gives the number of variables sensed to determine control valve position: a single-element regulator senses water level alone, a two-element regulator also senses steam flow, and a three-element regulator adds feedwater flow sensing.

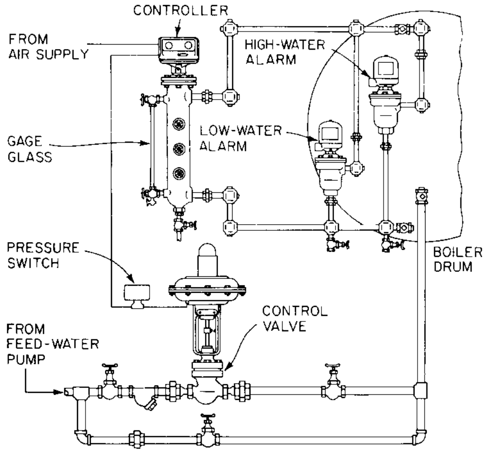

FIGURE 13 Boiler water level control system. In the controller, an external magnet senses position of displacer (Magnetrol).

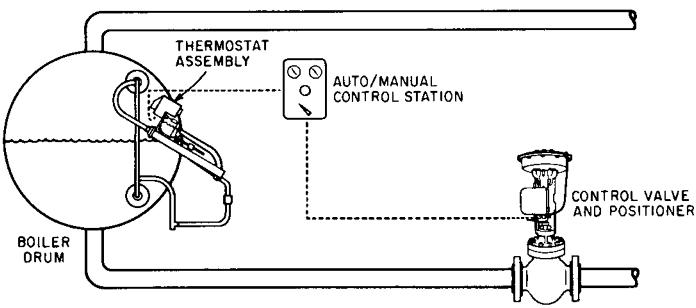

FIGURE 14 Single-element boiler feedwater regulator system (Copes-Vulcan)

For low-pressure boilers operating on moderate loads at no higher than 600 lb/in^2 (41 bar) gage and usually far below, on-off control of constant-speed pumps is sometimes used. The control can be similar to a low-water cutoff device actuated by float, but it has two switches: the switch at the higher water level is for level control, and the one below is for low-water cutoff of fuel and for alarm. Level differences of 1 to 3 in (2.5 to 7.6 cm) start the pump. This type of control can have a third switch, installed to give a separate alarm for low water before the fuel cutoff. With fire-tube boilers, the third switch can give a separate high-water alarm if the pump does not stop when the pump cutout switch is actuated.

Regulators directly actuated by float are also in use. Valves for these regulators are usually two-seated to reduce the thrust required of the float and linkage mechanism. Boiler pressures are low for this method, below 250 lb/in^2 (17 bar), although the regulators can be built to withstand 600 lb/in^2 gage (41 bar). Capacities go to more than 400,000 lb/h (180,000 kg/h) at pressure drops of 100 lb/in^2 (7 bar) across the valve.

For more demanding service, modulating control by means of an amplified signal applied to a valve actuator is necessary. The simplest type of modulating control of this kind is a single-element regulator, serving for fairly constant loads and pressures (Figures 13 and 14). In the pneumatic system, a change of water level in the boiler drum provides a pneumatic output signal that is transmitted to a controller supplying air pressure to the diaphragm or piston actuator of a control valve in the discharge line from the feedwater pump. A sensing thermostat for drum water level may be designed as a proportional controller, with gain changing in proportion to deviation from the set point. Linkage transfers the elongation of the sensing element to the pneumatic transmitter. Torque tubes or magnetic couplings (Figure 13) may also convert the water level sensing of a float or displacer to a pneumatic signal, in any of the standard pressure ranges. The air pressure required for the feedwater control valves must usually be at least 50 lb/in^2 gage (3.4 bar), and up to 125 lb/in^2 (8.6 bar) gage may be necessary. Balanced-trim valves do not require as high air pressures as do the unbalanced-plug type, and the small amount of leakage is not harmful.

In some single-element systems, the sensing element directly actuates the valve. In one system of this type, a high enough vapor pressure is produced in an enclosed tube to operate the feedwater control valve directly. The vapor pressure generator consists of a slanting inner tube mounted beside the boiler drum, with ends connected on top and bottom of the drum. A finned outer tube, filled with a liquid and connected only to the control valve actuator, envelops the inner tube. A decrease in water level brings more heating steam into the inner tube to warm the liquid in the outer tube and increase its vapor pressure. The vapor pressure is transmitted to the valve actuator to open to the valve.

In an electric control system, the level sensor can emit a signal modified by a slidewire potentiometer. The valve operator is an electric motor. In the larger sizes, the valve actuating speed will be low, so the system cannot respond quickly to rapid change in steaming rate and water level.

Some single-element systems employ a pressure control valve directly upstream of the main feedwater control valve. The upstream valve, called a differential valve, maintains a constant pressure on the feedwater control valve, improving its performance. Pressure control valves of this type have been used on some more advanced systems, too.

Single-element systems are inadequate for a boiler whose steaming rate changes suddenly because of the anomalous behavior of the water level during the change. A sudden demand for steam will reduce pressure in the drum, and steam bubble formation will increase, temporarily raising the water level at precisely the time when a falling level is required to signal for increased feedwater flow. The anomaly is called a rising water level characteristic. If the steaming rate change is gradual, the characteristic can be constant or even lowering.

The two-element regulator (Figure 15) solves this problem by sensing steam flow through an orifice in the steam main. The flow rate signal goes to the controller, and a sudden increase in steam flow will temporarily override the spurious water level signal.

Three-element control (Figure 16) offers a further refinement—it senses feedwater flow rate in addition to water level and steam flow rate. During a rapid and large load swing, the feedwater flow rate can then be adjusted to the steam flow rate, while the water level is simultaneously noted. The feedwater flow rate signal is converted to a linear signal for transmission to a computing relay that can be adjusted for the relative influences

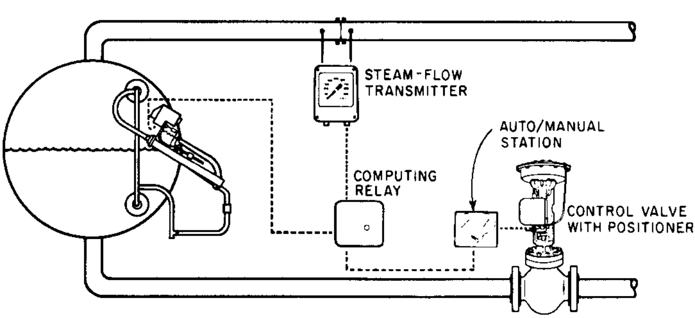

FIGURE 15 Two-element regulator system with steam flow measurement (Copes-Vulcan)

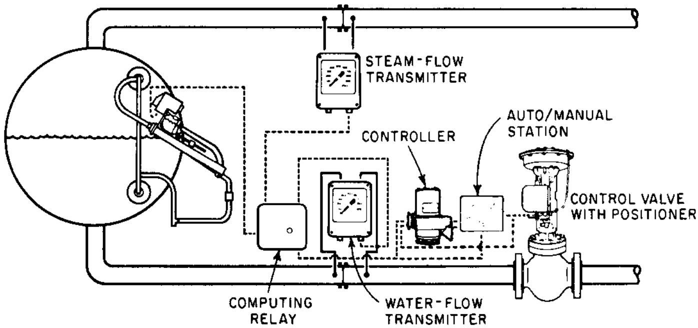

FIGURE 16 Three-element regulator system action depends on water level, steam flow, and feedwater flow (Copes-Vulcan).

of the three variables. A balanced signal then goes to the drum level controller, whose air output actuates the control valve. Three-element control systems can eliminate the effects of pressure variations upstream of the regulating valve.

BUILDING-WATER PRESSURE CONTROL In tall buildings or large industrial, commercial, or housing water systems, water pressure can be maintained in several ways. If elevated or pressure tanks are not desired, a multiple-pump system may be considered. The pumps can be constant-speed or variable-speed. For constant-speed pumps, pressure sensors bring in individual pumps as required to maintain pressure. If a large number of pumps are necessary, means must be provided to prevent all of them from starting simultaneously on restoration of power after a failure. (See Section 9.21.)

Hydropneumatic systems rely on air pressure in the top of a tank into which pumps deliver water intermittently. As water is drawn off, the air expands, reducing its pressure and eventually requiring another pump start. Both pressure and water level are sensed. If the pump liquid does not bring in enough air to the tank to make up for losses, an air compressor or the compressed-air system must supply air. Tank pressure after each level-controlled pumping cycle indicates whether more air is needed or whether air should be bled off. Float or probe sensors can determine liquid level, and various pressure sensors are available.

VALVES

For the final control element, conventional and traditional valves serve for on-off control in pump systems. They also cover much of the modulation need. In recent years, modulating control in demanding services has required development of special control valves, actuators, and accessories. System dynamic characteristics, corrosion, erosion, noise, and costs have influenced the development.

Operation and Valve Types The on-off operation of pump valves serves for

1. Isolation of a pump: protection, maintenance, removal, administrative reasons
2. Bypass or partial isolation: inlet or outlet block for protection, improved flow control, administrative reasons
3. Pressure relief: protection
4. Venting: removal of gases and vapors from the casing
5. Draining: removal of liquids from the casing

The modulating mode of operation services for

1. Control of flow rate to pump or of pressure at inlet
2. Control of delivered flow rate or pressure
3. Control of bypass flow rate

Auxiliary flows in lines to packing boxes, seals, and sensing or measuring elements are controlled by either on-off or modulating valves.

The principal types of valves for on-off and much modulating service are

- Gate (rare for modulating)
- Globe (and angle)
- Butterfly
- Ball
- Eccentric butterfly
- Plug
- Diaphragm

Check valves and relief valves, although possessing design features peculiar to their nature, make use of the essential features of globe and butterfly valves.

Control valves have developed as a special group for demanding services that require wide modulation range, stability, wear resistance, low noise, or a specific flow characteristic. Ingenuity and experience have combined to evolve many unusual but effective designs, each with advantages and drawbacks.

Control Valves A control valve is a valve that modulates the flow through it to provide the desired downstream (or upstream) pressure, flow rate, or temperature. Although most types of valves can be partly closed and thus give a degree of control that may be acceptable for many purposes, the term *control valve* has come to mean a specialized type of power-actuated valve designed for good performance under steady-state or dynamic flow conditions.

Before examining various control valves and their reasons for existence, some basic practical concepts must be reviewed. A control valve includes

1. A body to contain the pressure, direct the liquid flow, and resist loads from piping and actuation
2. A variable orifice or orifices
3. A steam for positive connection of orifice elements to actuator
4. A piercement through the body wall to allow the steam to pass
5. An actuator to adjust the orifice size

Adaptations of globe valves and angle valves are common. These forms inherently give tight shutoff. High-quality trim helps resist erosion and wear at low flow rates when the orifice is nearly closed. Support is often provided for the steam to prevent vibration and flutter (Figure 17). The plug can be characterized (shaped to give certain rates of flow for given percentages of opening) as desired. The support of the stem is usually on the bonnet side of the orifice rather than opposite, to keep orifice size down. With flow upward (through the orifice, and then past the plug), the actuator must overcome upstream pressure to close the valve. With flow downward (past the plug, and then through the orifice), valve motion becomes unstable when the valve is nearly closed.

The basic globe valve is often modified to put two orifices and plugs on the same stem, with the upstream fluid entering the space between and passing in two opposite flows

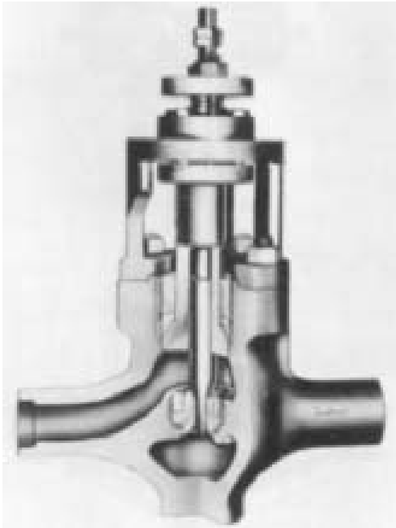

FIGURE 17 This control valve is basically a globe type, with reduced trim and guided tapered plug (Copes-Vulcan).

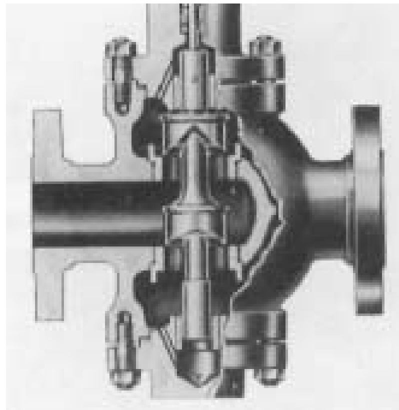

FIGURE 18 Double-seated control valve with characterized plugs (Masoneilan International)

through the two orifices. This is the double-seated valve (Figure 18). Actuator force is greatly reduced because fluid pressure tends to open one plug and close the other. The balance is not complete, however, because one orifice is usually larger than the other to permit assembly and because there is a difference in head conversion effects in the orifices at low flow rates.

Addition of an internal diaphragm and a port in the body near one orifice makes the valve a three-way type, able to divide flow between two outlet lines or, with reversed flow direction, combine two flows in a desired ratio. The double-seated valve cannot seal tightly because of manufacturing tolerances and thermal and pressure effects on the valve body.

Butterfly valves can modulate flow (Figure 19). Special vane shapes have been introduced to improve performance. Elastomer or plastomer linings give a tight shutoff on liquids within the temperature range of the materials.

Ball valves as control valves may take conventional form, with an actuator and positioner atop the valve. In other designs, the ball may be merely a fraction of a spherical shell, adequate for sealing on the customary tetrafluoroethylene seat ring but with its edge shaped to develop the required characterized flow as the shell rotates and exposes the orifice. Convex, V-notch, and parabolic edge shapes find use. The conventional ball valve has two variable orifices in series, of course, with a small chamber between them in which some head recovery occurs as fluid momentarily slows.

A specialized form of gate valve can serve as a control valve. This type contains a multiple-orifice plate mounted permanently as a diaphragm perpendicular to the line of flow (Figure 20). The "disk," a plate that also contains two or more slotted orifices, is mounted to slide vertically across the upstream side of the stationary plate. The degree of orifice coincidence determines the flow rate. Actuation is by a pin mounted on the stem and protruding through the stationary plate into a pocket on the sliding plate. Low vibration and straight-through flow are characteristic of this valve. The actuating force is low at all flow rates because of the sliding action of the lapped disk and plate and because of the disk support. Both disk and plate are made of stainless steel or other alloys.

CAGE VALVES This type has developed into an entire group of control valves (Figures 21 to 25). The valve body closely resembles that of the globe valve, with a large orifice in a

FIGURE 19 Butterfly control valve with linkage connecting spindle to diaphragm actuator and positioner (Masoneilan International)

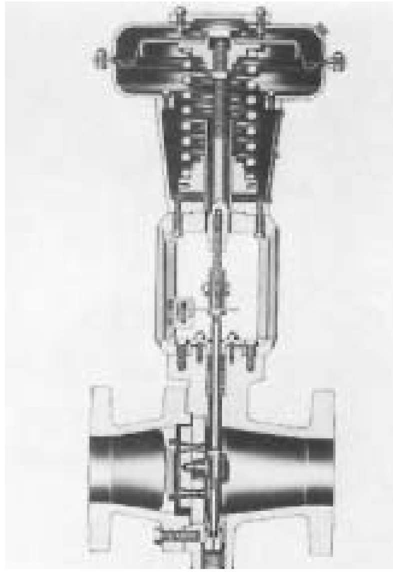

FIGURE 20 Movement of one plate past another opens or closes flow orifices in this control valve (Jordan Valve Division, Richards Industries).

horizontal area of the central diaphragm. The cage is a hollow cylinder that is held between the bonnet and the edge of a hole in the diaphragm. The disk or plug, sliding up and down inside the cage, is guided by it.

In most cage valves, the lower zone of the annular cage is available for flow control orifices, alternately exposed and covered as the plug moves up and down (Figure 21). Tight shutoff at these orifices is impossible, of course, and so the bottom of the cage or a separate seat ring is machined and finished to match a seating surface on the plug.

In other cage valves, where the plug may be much smaller than the cage inside diameter (Figure 22), all control action is at the lower seat ring. The plug guiding is then on the stem or in the seat ring orifice, and the holes in the cage are merely passage holes to distribute the liquid evenly around the perimeter.

The seat ring in cage valves is retained by bonnet bolting forces acting through the cage. Gaskets take up tolerances in dimensions and finish, so the seat ring need not be pressed or screwed into the valve diaphragm.

The ordinary cage valve has several advantages. Suitable machining of cage holes can give the valve the desired characteristics. Removal and replacement of internals, such as cage and seat ring, are quick and simple. A vertical hole through the plug makes the valve nearly balanced (Figure 23), although considerable leakage can occur between plug and cage wall if the plug is balanced in this way. Cage wall orifices vary not only in number, size, and cross-sectional form, but also in path and surface roughness.

In one advanced variation of the cage valve, the cage wall is comparatively thick and the many pathways through it are labyrinthine, with several right-angle turns and several orifices and expansion chambers in each pathway (Figure 26). To make the cage practical from a manufacturing standpoint, it consists of a series of thin disks each carrying a pattern of labyrinthine paths in one surface. The opposite surface is flat, so when the disks are stacked into a cage, the paths are sealed from one another. Flow in valves of this type can be from inside or outside the cage. Characterization is possible by such means as a change in the number of orifices per disk at various heights in the stack. As in conventional cage

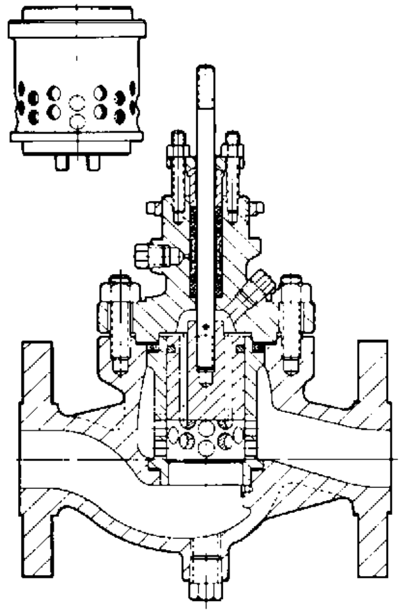

FIGURE 21 Hole pattern in cage can reduce noise and cavitation (ITT Hammel Dahl Conoflow).

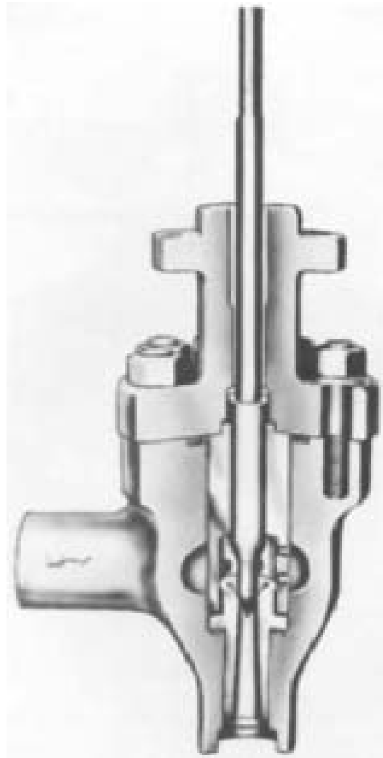

FIGURE 22 Tapered outlet section improves flow pattern in this cage valve (Copes-Vulcan).

valves, the trim and characterization can be quickly changed after bonnet removal. The bonnet bolting, outside the liquid, holds the cage elements in place.

In other cage valves, the passage walls may be wavy, resembling screw threads. This assists in noise reduction in gas valves.

MULTIPLE ORIFICES IN SERIES Several valves have orifices in series rather than in parallel; the principle is called *cascading.* In one group, a tapered plug with a series of circumferential serrations moves in a tapered seat that may be either conical or stepped (Figures 27 and 28). In either case, the serrations or steps produce a series of small annular chambers alternating with annular restrictions that serve as orifices. Some alternating change in flow direction also occurs to create the desired head loss.

In another group, annular chambers in the wall of a cylindrical cage are separated from one another by ridges that are a close fit with annular ridges on a sliding plug. The orifices narrow as the ridge sets approach one another, whereas the expansion chambers remain nearly constant in size. Repeated change in flow direction and speed produces head loss. In a variation of this type (Figure 29), the chambers on the cylindrical plug are short, steeply angled helical cuts, so the liquid takes a helical path. The purpose is to fling the liquid against the walls of the cage and displace cavitation bubbles toward the center and away from wall contact. Shutoff in these valves cannot rely on the multiple-orifice systems, but instead depends on a separate conventional seat and plug surface, either upstream or downstream of the orifice system.

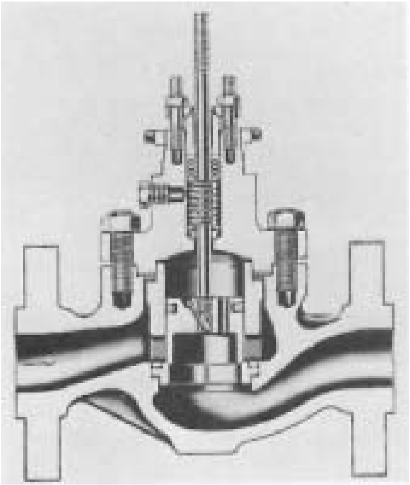

FIGURE 23 Holes in plug allow pressure balance in this cage valve (Fisher Controls).

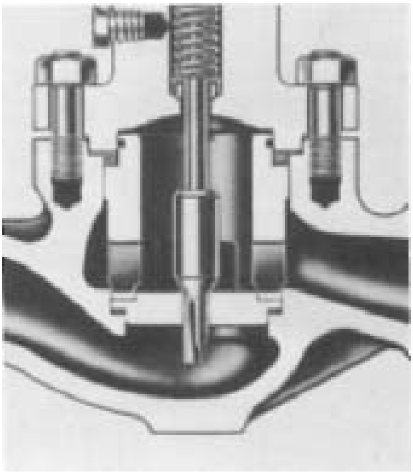

FIGURE 24 An extreme in reduced trim for a cage valve (Fisher Controls)

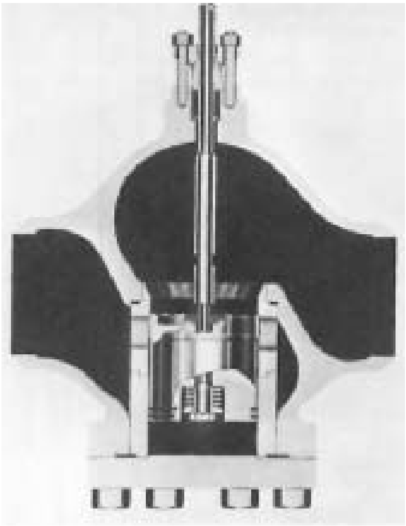

FIGURE 25 Cage valve with bottom access (Copes-Vulcan)

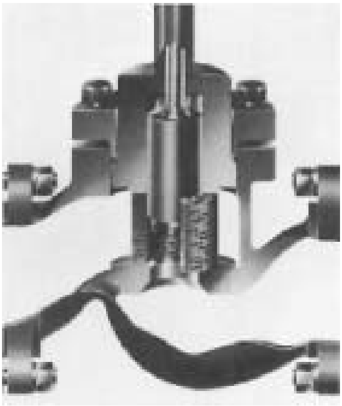

FIGURE 26 Control valve with flow through labyrinthine orifices in built-up cage (Control Components)

Many of these special valves are very expensive because of the multiplicity of complicated parts and because of the reduction in capacity caused by the advanced design. Larger bodies and overall sizes are required for a given flow rate. In pump control, the valves see service on high-pressure feedwater pump minimum-flow recirculating lines, where pressures go as high as 6000 lb/in^2 (400 bar) and water temperatures range to 500°F (260°C). Tight shutoff over thousands of operating cycles is the goal.

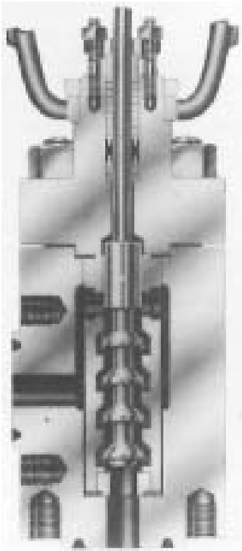

FIGURE 27 Pressure breakdown occurs across several annular orifices and direction changes in this valve (Masoneilan International).

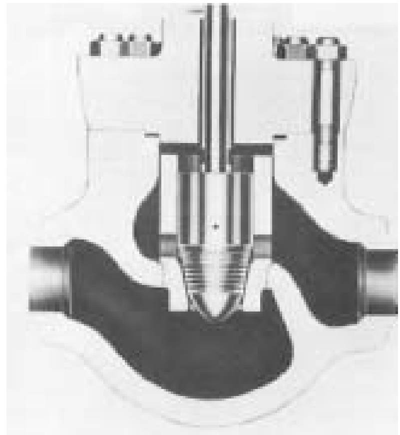

FIGURE 28 Serrations on large plug give high pressure drop at low flow (Copes-Vulcan).

FIGURE 29 Pump bypass flow at high pressure drop results when line flow at top ceases and mechanism opens valve at right (Yarway).

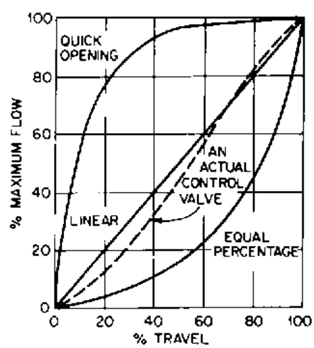

FIGURE 30 Basic control valve characteristics. Valves are designed to approach these.

FLOW CHARACTERISTICS An important parameter for valves in modulating control is the flow characteristic of the valve, often called simply the characteristic. The flow characteristic expresses the way in which the flow through the valve depends on percentage of valve stem travel. The latter may be translatory or rotary motion, of course. A plot of percentage of maximum flow at various percentages of stem travel is the usual quantitative way of showing a characteristic (Figure 30). Several types of characteristics have become common, either because of inherent desirability or because familiar and traditional types of valves have them.

The linear characteristic is a straight line, with flow percentage always equal to stem travel percentage. A quick-opening characteristic, on the other hand, produces proportionately more flow in the early stages of stem travel. An equal-percentage characteristic gives a change that, for a given percentage of lift, is a constant percentage of the flow before the change. A change of 16% of total stem travel will double the flow, so at a stem travel of about 84%, flow will be 50% of maximum.

Although the linear characteristic would seem best because the rate of flow change is uniform for a given stem travel change, incorporation of the valve into a piping system affects the decision. Because resistance to flow in a given piping system is roughly proportional to the square of the flow rate, the curve of the piping system head loss plotted against flow rate will be a parabola, with resistance increasing at a faster rate than flow. If the piping system and valve are considered together and the flow rate in the system plotted against percentage of valve stem travel, the overall system characteristic will differ from the valve characteristic. The overall system characteristic is displaced upward toward the quick-opening valve characteristic but can have points of flexure. The amount of displacement depends on what part of the total system pressure drop is taken by the valve. Only with a very short outlet pipe would the valve take all the pressure drop, and then its characteristic would be that of the system.

In many systems, the pressure drop across the valve is designed to be from one-tenth to one-third of the total system drop. If the valve in such a system has an equal-percentage characteristic, the characteristic of the overall system will be close to linear as far as the actuator of the valve is concerned (Figure 31).

The equal-percentage characteristic is obtained by such measures as contouring the valve plug, contouring slots in plug skirt or cage, or suitably spacing holes in the cage.

Valves with a characteristic between linear and equal-percentage are also useful in modulating control. Ball, plug, and butterfly valves are examples. Characterized ball and plug valves are examples of modifications for control characteristic purposes.

RANGEABILITY Control valve rangeability (Figure 32) can be important in some cases; it is defined as the ratio of maximum flow to minimum flow at which the valve characteristic is still evident and control is possible. A high rangeability value means that a single valve can handle low as well as high flows, so auxiliary valves are unnecessary. The best performance in this regard is about 100:1 for special designs under favorable circumstances, and 25:1 is common for conventional valves and ordinary circumstances.

Connected with rangeability is *valve gain,* which is the slope of the flow characteristic curve at any point. In practical terms, valve gain is the change in flow rate per unit of

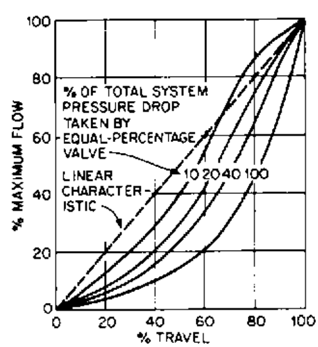

FIGURE 31 For a valve in a system, the overall characteristic depends on valve characteristic and pressure breakdown.

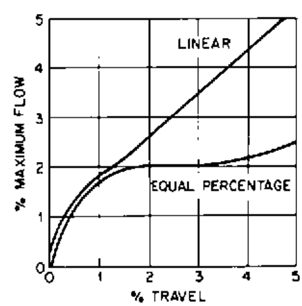

FIGURE 32 Rangeability of a valve is determined by the point at which valve characteristic is still evident, between 1 and 2% of maximum flow for the two valve characteristics shown here.

change in stem travel. A high gain means that a slight movement of the stem causes a large change in flow rate, so instability occurs more readily. This sets a limit on a valve's rangeability. The quick-opening valve, with a high gain in the nearly closed position, is unsuitable for many modulating tasks.

Valves with approximately an equal-percentage flow characteristic are considered most suitable for the majority of flow control tasks; valves with a linear characteristic are preferred for some applications.

SIZE The *size* of a valve is an indefinite concept. In the past, a valve's size was understood to be the pipe size of the line connected to it. Venturi valves with tapered end passages leading to reduced-diameter orifices and valves in which the orifice area is reduced for reasons such as cost-cutting, characterization, and special advantages have forced users to rate valve size in other terms. A statement of maximum orifice area might be a way to express size, but this too would be ambiguous because the head losses in partial recovery after the orifice are not the only losses in the valve. In addition, the valve may have two or more orifices in series, and the geometry of the orifice itself may affect results.

FLOW COEFFICIENT The valve flow coefficient C_v (K_v in SI units) is now a frequently used parameter for valve size. It is the number of gallons per minute (cubic meters per hour) of 60°F (15.6°C) water that will flow through a valve at a 1-lb/in^2 (1-bar) pressure drop across the valve. The upstream test pressure is also stated. The maximum C_v (K_v), found with the valve fully open, is widely accepted as a measure of valve size. To find the maximum liquid flow rate of a valve at any pressure drop and with a liquid of any specific gravity, the equation is

in USCS units
$$Q = \frac{C_v}{(G_t/\Delta P)^{1/2}}$$

in SI units
$$Q = \frac{K_v}{(G_t/\Delta P)^{1/2}}$$

where Q = flow rate, gpm (m^3/h)
C_v = valve flow coefficient in USCS units
K_v = valve coefficient in SI units
G_t = specific gravity of the liquid
ΔP = pressure drop across valve, lb/in^2 (bar)

PRESSURE RECOVERY AND CAVITATION A drop in liquid pressure upon passing through a valve is recovered to varying extent downstream (Figure 33). The degree of recovery

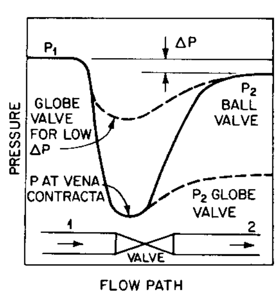

FIGURE 33 For a given pressure drop DP across a valve, the globe will show a higher pressure at the vena contracta, making it more likely that cavitation difficulties will be avoided when the vapor pressure is high.

depends on valve type: ball and butterfly valves have higher recovery percentages than do globe and angle valves. To avoid cavitation, which is the formation of vapor bubbles near the *vena contracta* of the valve, followed by a sudden damaging collapse near the metal, the static pressure at the *vena contracta* must be above the liquid vapor pressure. This is easier to do with a low-recovery valve because the initial pressure drop need not be as high for a given downstream pressure. Several factors have been devised to indicate pressure recovery. One, C_f, the critical flow factor, is the ratio of pressure recovery, varying for different valve openings. Another, K_m, the valve recovery coefficient, is the ratio of pressure drop across the valve to pressure drop between valve inlet and *vena contracta* at that instant when flow begins to be choked by bubble formation. Both of these factors will be higher for globe valves than for ball and butterfly valves, and the factors serve to indicate valve suitability for marginal cavitation service.

ACTUATORS The motion needed to change the valve orifice area and to close the valve tightly is produced by an actuator. The types of motion of the valve plug or disk are either linear or rotary (Figure 34), the latter being usually 90° but occasionally as low as 70°. These motions can be effected in several ways. The linear translating motion can result from a cylinder or diaphragm actuator working directly or through linkage (Figure 35). A screw thread at the stem top can convert a rotary motion to linear stem motion, or threads at the stem bottom can engage threads in the valve disk so rotation of the stem moves the disk. Geared electric motor drives (Figure 36), cylinders (Figure 37), and diaphragm-and-spring actuators (Figure 38) are common with ball, plug, and butterfly valves. The solenoid valve (Figure 39) relies on an electromagnetic force to move a disk directly or to initiate the piloting action that allows line fluid to open the valve. The piloted solenoid valve (Figure 40) relies on fluid pressures to open the main orifice.

The simplest actuator is the manually powered operator, which is a gear box. It provides enough mechanical advantage to overcome starting friction and to seal the valve tightly. Provision for an impact blow to initiate opening is found in some operators.

The choice of actuator depends first on whether the service is on-off or modulating. For on-off service, the actuator need have only enough force to overcome breakaway force or torque and sufficient stroke to open the valve fully. Speed of operation is rarely critical, and motion limits can be designed into valve or actuator. Pneumatically (Figure 41) and hydraulically powered actuators usually stroke rapidly but can be slowed in either direction by auxiliary valving or controls. On some pneumatic actuators, times to five minutes are possible. Electric-motor-driven actuators are slower than pneumatic or hydraulic types and require limit switches to stop the motor at the end of travel.

In modulating service, where the actuator must hold a control valve setting, demands are more severe. The speed of movement, expressed as stroking speed, is sometimes an important factor, especially in emergency shutdown or bypass. The stability of an actuator is partly its ability to hold the valve setting under fluctuating or buffeting

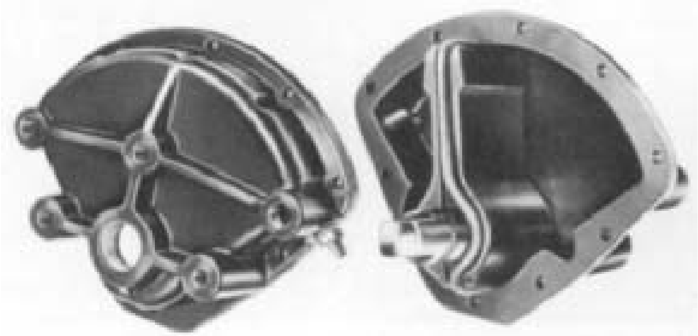

FIGURE 34 Rotary actuator with sealed blade (Vomox)

FIGURE 35 Linkage connects actuator and valve stem (Masoneilan International)

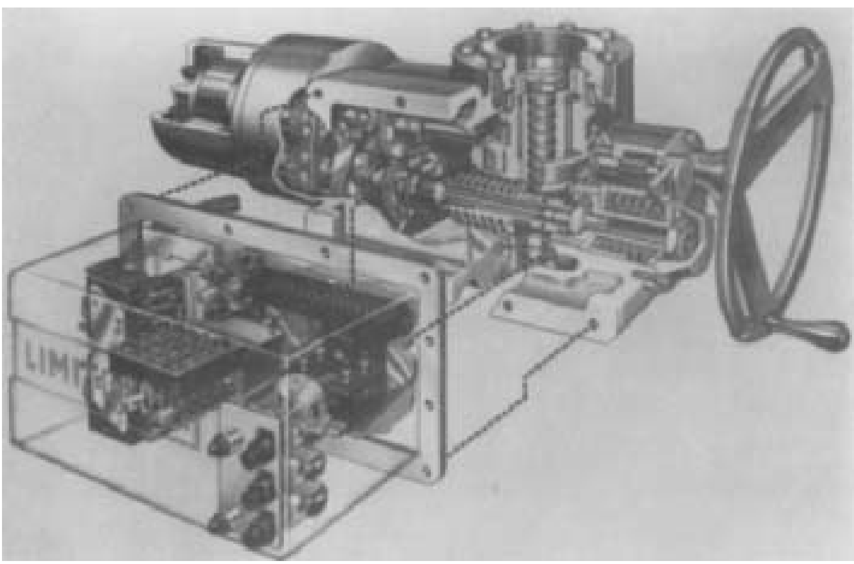

FIGURE 36 Electric-motor-driven actuator with mechanism for limiting torque (Philadelphia Gear)

loads from the fluid. Damping and high spring rate can help with this. The relation of the natural frequency of the actuator and its adjacent elements to the frequencies encountered in controlling the flow or those experienced from fluid buffeting can also be important.

Stroke length is also a factor. Although the disk in a globe valve or similar type need lift only one-quarter of the seat diameter to give adequate area for full flow, this distance in large valves will exceed the 2-in (5-cm) stroke of most diaphragm actuators. If linkage

FIGURE 37 Cylinder actuator and linkage for ball valve (Jamesbury)

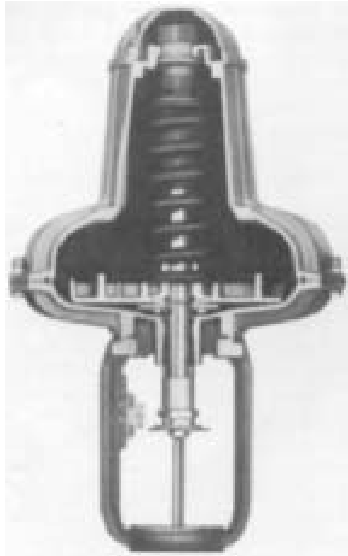

FIGURE 38 Diaphragm-and-spring actuator, reversible type (Foxboro)

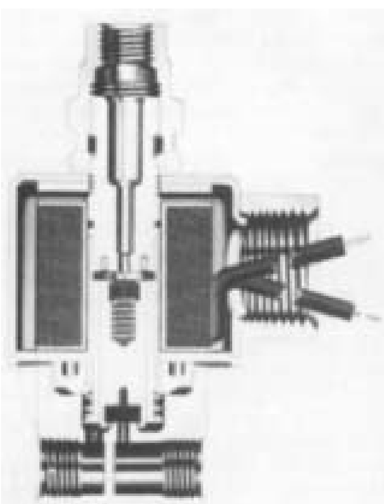

FIGURE 39 Solenoid valve for three-way operation is direct-acting (Skinner Precision Industries).

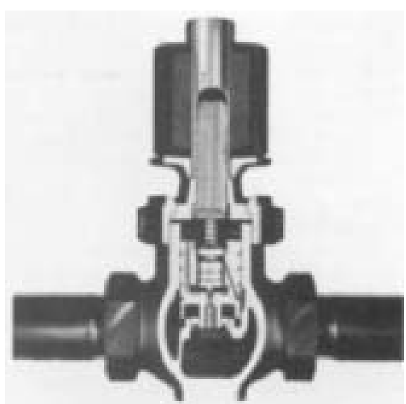

FIGURE 40 Piloted solenoid valve relies on fluid pressure to open main orifice (Magnetrol Valve).

with its lever advantage is needed to increase thrust, the problem becomes more acute. A cylinder or electric actuator is then necessary.

The source of power for the actuator influences choices too. One standard may be 3- to 25-lb/in^2 (0.2- to 1.7-bar) instrument air pressure, whereas in other cases much higher air or oil pressure is available.

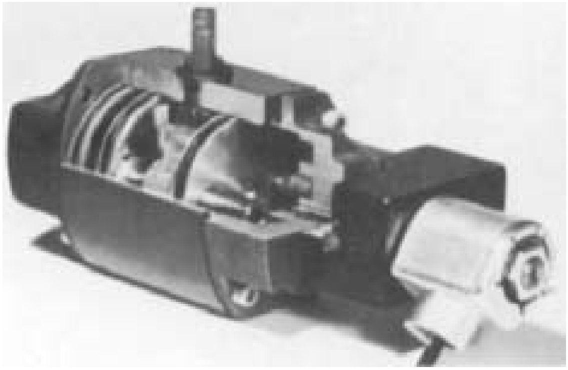

FIGURE 41 Opposed pistons drive rack-and-gear mechanism for 90° rotation in this pneumatic actuator (Worcester Controls).

The diaphragm-and-spring actuator (Figure 38) is a very common type and has several important advantages. The spring can be pre-loaded to cause the valve to either close or open fully (be fail-safe) if control air fails. The spring also opposes the force generated by the control signal, doing so in a manner giving proportional control. Of course, the spring's opposition negates much of the force available on the diaphragm, but the simplicity and low friction of this actuator have made it very popular. Most modern types are reversing: The fail-safe action can easily be changed from open to close by turning the diaphragm enclosure upside down and reassembling.

POSITIONERS With actuators that lack an internal spring, a positioner is needed to adjust the valve position to the desired value. A positioner is a small feedback system that receives an input signal (usually air pressure but sometimes an electric signal) from a controller and adjusts a valve stem position to a prearranged corresponding value. The valve stem position, which is the output, need not vary linearly with input pressure; cams in the mechanism can give a wide range of stem position functions and thus apparently change the characteristic of the valve.

The positioner is a necessity for actuators in which the valve stem position is not a function of the actuator fluid pressure or electric current magnitude. Examples are pneumatic and hydraulic cylinders and electric motors. Even though positioners are not inherently necessary on the diaphragm-and-spring actuator, they are sometimes applied. The reasons for the application hold for other types of actuators, too.

Friction in the actuator diaphragm cylinder or valve stem packing is one reason. The positioner can cut the dead-band from values such as 5 to 15% to less than 0.5% and can give repeatability of 0.1% of full span.

Need for more force to close a single-seat valve tightly is another reason for using a positioner. If loading pressure must be increased above a standard 15 lb/in^2 gage (1-bar) value, the positioner can control air at a higher pressure and thus greatly increase the stem force.

Split-range operation, in which different valves operate over different parts of the controller output pressure range, calls for positioners. Reversal of valve action, too, is easily achieved with positioners. A positioner can also speed up valve response because the low-volume positioner will act faster than the high-volume valve actuator and can open a larger air supply than that in the controller. A pneumatic amplifier or booster is an alternative way to do this. Finally, change in control valve characteristic, such as from linear to equal-percentage, is also possible through a positioner cam.

Because a positioner is another control loop added to a system, its effect under dynamic conditions may worsen overall performance. If changes or oscillations are slow, the positioner and actuator will follow them accurately and correct for them. For rapid changes, however, the effect of the positioner can be harmful. Evidence shows that if the natural fre-

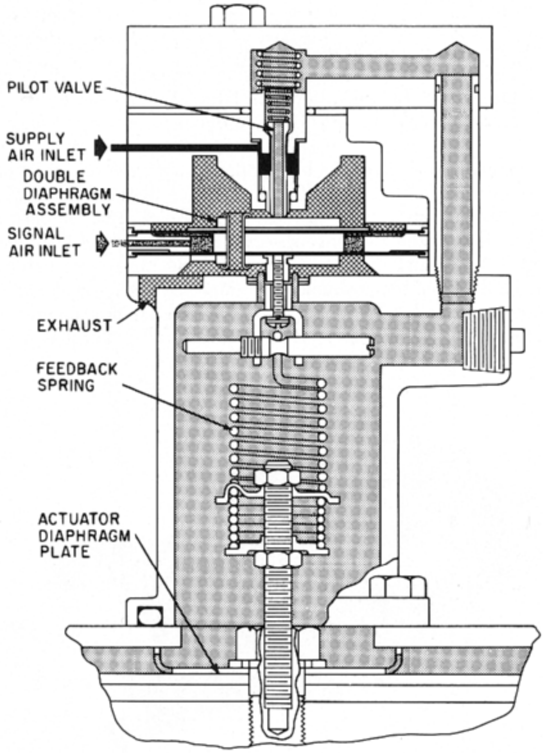

FIGURE 42 Force-balance positioner with spool and sleeve pilot valve (Masoneilan International)

quency of the complete process control loop is more than 20% of the frequency at which the gain in the positioner-actuator system is attenuated 3 dB, the positioner will impair system performance. Liquid level control systems are more likely to benefit from positioners than are flow or pressure control systems.

Pneumatic positioners may be classified as force-balance or motion-balance types. In the force-balance type, the force in the range spring inside the positioner is balanced against control air pressure inside a bellows or double-diaphragm assembly. In the force-balance positioner of Figure 42, the feedback spring, which can be adjusted for range of pressure and initial actuation pressure, is attached to the actuator diaphragm plate at the bottom and to a double-diaphragm assembly at the top. The upper diaphragm has twice the area of the lower; introduction of signal air from the controller into the space between the two diaphragms forces the assembly upward very slightly but enough to lift a pilot valve at the positioner top and allow supply air pressure to flow through and downward past the feedback spring to press the actuator diaphragm down until forces balance. A reduction in signal pressure allows the double-diaphragm assembly to move downward, first closing the pilot valve and then exposing a hole through the pilot valve stem. Air then bleeds out from the actuator to atmosphere until forces are again in balance.

In the force-balance positioner of Figure 43, flexure strips and a bell crank convert the vertical actuator motion to a horizontal motion in the double-diaphragm assembly at the top left and the supply valve at the right.

A motion-balance positioner showing the application of a cam to impart a characteristic is shown in Figure 44. The cam at the lower right is pivoted and caused to rotate by the

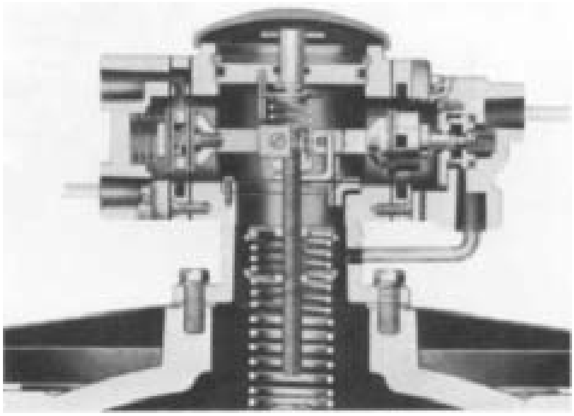

FIGURE 43 Force-balance positioner with flexure linkage (ITT Hammel Dahl Conoflow)

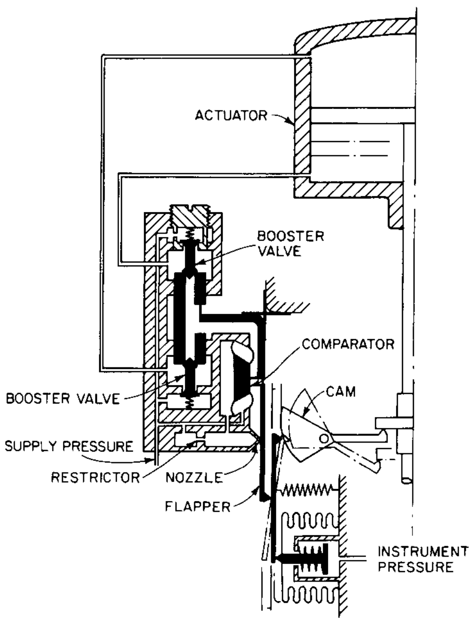

FIGURE 44 Motion-balance positioner with cam and diaphragm comparator (ITT Hammell Dahl Conoflow)

actuator stem motion. Supply pressure enters the valve assembly block at the left and goes to both booster valves. It also bleeds through a restrictor and nozzle at the bottom of the valve assembly block. The position of the flapper before the nozzle determines the pressure in the diaphragm comparator at the right of the valve assembly block. An increase in signal air pressure to the bottom bellows moves one end of a balance beam and pushes the flapper closer to the nozzle. This builds pressure in the diaphragm comparator and moves it to the right. A linkage transforms this motion into a motion that opens the booster valve

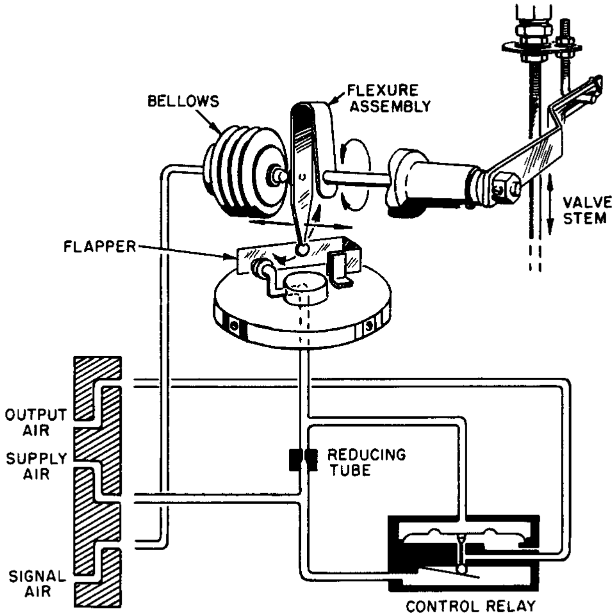

FIGURE 45 Motion-balance positioner with flexure assembly (Foxboro)

to supply air to the cylinder actuator top and permits air to exhaust from the cylinder bottom. The actuator stem moves down until the feedback cam, aided by the comparator linkage, has repositioned the flapper in front of the nozzle.

In another motion-balance positioner (Figure 45), signal air pressure from 3 to 15 lb/in^2 (0.2 to 1 bar) gage in a bellows opposes a flexure assembly on a shaft that is rotated by the valve stem motion. An increase in signal air pressure to the bellows expands it and moves the lower end of the flexure away from a flapper, permitting the flapper to move toward a nozzle. The resultant buildup of air pressure on the diaphragm of the control relay at the lower right closes the exhaust port and opens the supply port to allow air at fully supply pressure to pass to the actuator. The valve stem motion rotates the flexure and thereby shifts the tip touching the flapper. The flapper assumes an equilibrium position proportional to the signal air pressure.

The pneumatic amplifier or booster is a special kind of regulator valve that develops an output air pressure proportional to the input signal pressure. It can be used to boost pressure on an actuator for faster action in cases where the instrument tubing is small-bore and long and the actuator volume is large.

FURTHER READING

ISA Handbook of Control Valves, Instrument Society of America, Pittsburgh, 1971.