

CHAPTER 46

VALVES

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FUNDAMENTALS

**V**ALVES are the manual or automatic fluid-controlling elements in a piping system. They are constructed to withstand a specific range of temperature, pressure, corrosion, and mechanical stress. The designer selects and specifies the proper valve for the application to give the best service for the economic requirements.

Valves have some of the following primary functions:

- Starting, stopping, and directing flow
- Regulating, controlling, or throttling flow
- Preventing backflow
- Relieving or regulating pressure

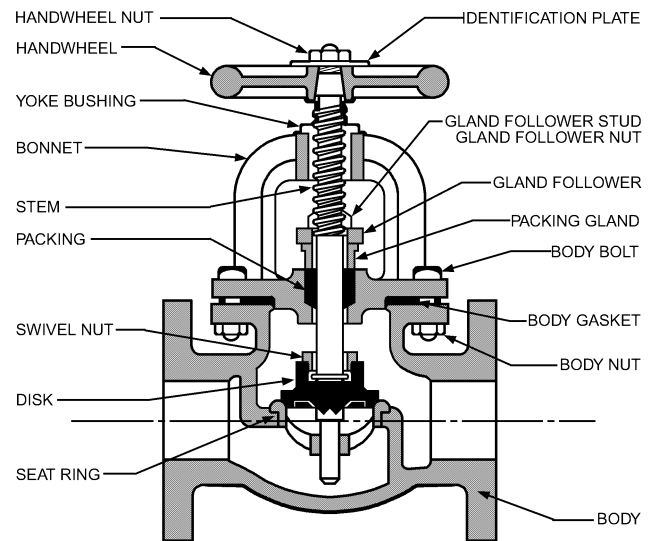
The following service conditions should be considered before specifying or selecting a valve:

1. Type of liquid, vapor, or gas
  - Is it a true fluid or does it contain solids?
  - Does it remain a liquid throughout its flow or does it vaporize?
  - Is it corrosive or erosive?
2. Pressure and temperature
  - Will these vary in the system?
  - Should worst case (maximum or minimum values) be considered in selecting correct valve materials?
3. Flow considerations
  - Is pressure drop critical?
  - Should valve design be chosen for maximum wear?
  - Is the valve to be used for simple shutoff or for throttling flow?
  - Is the valve needed to prevent backflow?
  - Is the valve to be used for directing (mixing or diverting) flow?
4. Frequency of operation
  - Will the valve be operated frequently?
  - Will valve normally be open with infrequent operation?
  - Will operation be manual or automatic?

Nomenclature for basic valve components may vary from manufacturer to manufacturer and according to the application. [Figure 1](#) shows representative names for various valve parts.

Body Ratings

The rating of valves defines the pressure-temperature relationship within which the valve may be operated. The valve manufacturer is responsible for determining the valve rating. ASME *Standard B16.34* should be consulted, and a valve pressure class should be identified. Inlet pressure ratings are generally expressed in terms of the ANSI/ASME class ratings and range from ANSI Class 150 through 2500, depending on the style, size, and materials of construction, including seat materials. Automatic control valves are usually either Class 125 or Class 250. Tables in the standard and



**Fig. 1 Valve Components**  
(Courtesy Anvil Int'l.)

in various books show pressure ratings at various operating temperatures (ASME *Standard B16.34*; Lyons 1982; Ulanski 1991).

Materials

ASME *Standard B16.34* addresses requirements for valves made from forgings, castings, plate, bar stock and shapes, and tubular products. This standard identifies acceptable materials from which valves can be constructed. In selecting proper valve materials, the valve body-bonnet material should be selected first and then the valve plug and seat trim.

Other factors that govern the basic materials selection include

- Pressure-temperature ratings
- Corrosion-resistance requirements
- Thermal shock
- Piping stress
- Fire hazard

Types of materials typically available include

- Carbon steel
- Ductile iron
- Cast iron
- Stainless steels
- Brass
- Bronze
- Polyvinyl chloride (PVC) plastic

**Bodies.** Body materials for small valves are usually brass, bronze, or forged steel and for larger valves, cast iron, cast ductile

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iron, or cast steel as required for the pressure and service. Listings of typical materials are given in Lyons (1982) and Ulanski (1991).

**Seats.** Valve seats can be machined integrally of the body material, press-fitted, or threaded (removable). Seats of different materials can be selected to suit difficult application requirements. The valve seat and the valve plug or disk are sometimes referred to as the valve trim and are usually constructed of the same material selected to meet the service requirements. The trim, however, is usually of a different material than the valve body. Replaceable composition disks are used in conjunction with the plug in some designs in order to provide adequate close-off.

Maximum permissible leakage ratings for control valve seats are defined in Fluid Controls Institute (FCI) *Standard 70-2*.

**Stems.** Valve stem material should be selected to meet service conditions. Stainless steel is commonly used for most HVAC applications, and bronze is commonly used in ball valve construction.

**Stem Packings and Gaskets.** Valve stem packings undergo constant wear because of the movement of the valve stem, and both the packings and body gaskets are exposed to pressure and pressure variations of the control fluid. Manufacturers can supply recommendations regarding materials and lubricants for specific fluid temperatures and pressures.

### Flow Coefficient and Pressure Drop

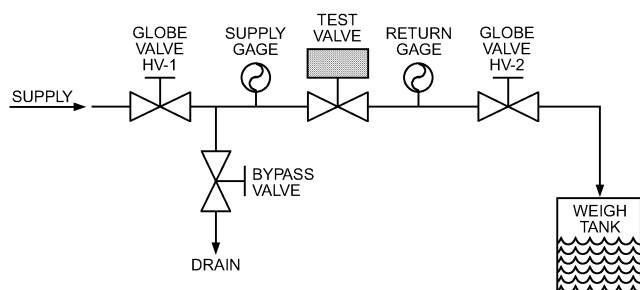
Flow through any device results in some loss of pressure. Some of the factors affecting pressure loss in valves include changes in the cross section and shape of the flow path, obstructions in the flow path, and changes in direction of the flow path. For most applications, the pressure drop varies as the square of the flow when operating in the turbulent flow range. For check valves, this relationship is true only if the flow holds the valve in the full-open position.

For convenience in selecting valves, particularly control valves, manufacturers express valve capacity as a function of a flow coefficient  $C_v$ . By definition in the United States,  $C_v$  is the flow of water in gallons per minute (at 60°F) that causes a pressure drop of 1 psi across a fully open valve. Manufacturers may also furnish valve coefficients at other pressure drops. Flow coefficients apply only to water. When selecting a valve to control other fluids, be sure to account for differences in viscosity.

**Figure 2** shows a typical test arrangement to determine the  $C_v$  rating with the test valve wide open. Globe valve HV-1 allows adjusting the supply gage reading (e.g., to 10 psi); HV-2 is then adjusted (e.g., to 9 psi return gage) to allow a test run at a pressure drop of 1 psi. A gravity storage tank may be used to minimize supply pressure fluctuations. The bypass valve allows fine adjustment of the supply pressure. A series of test runs is made with the weighing tank and a stopwatch to determine the flow rate. Further capacity test detail may be found in International Society for Measurement and Control (ISA) *Standard S75.02*.

### Cavitation

Cavitation occurs when the pressure of a flowing fluid drops below the vapor pressure of that fluid (**Figure 3**). In this two-step



**Fig. 2** Flow Coefficient Test Arrangement

process, the pressure first drops to the critical point, causing cavities of vapor to form. These are carried with the flow stream until they reach an area of higher pressure. The bubbles of vapor then suddenly collapse or implode. This reduction in pressure occurs when the velocity increases as the fluid passes through a valve. After the fluid passes through the valve, the velocity decreases and the pressure increases. In many cases, cavitation manifests itself as noise. However, if the vapor bubbles are in contact with a solid surface when they collapse, the liquid rushing into the voids causes high localized pressure that can erode the surface. Premature failure of the valve and adjacent piping may occur. The noise and vibration caused by cavitation have been described as similar to those of gravel flowing through the system.

### Water Hammer

Water hammer is a series of pressure pulsations of varying magnitude above and below the normal pressure of water in the pipe. The amplitude and period of the pulsation depend on the velocity of the water as well as the size, length, and material of the pipe.

Shock loading from these pulsations occurs when any moving liquid is stopped in a short time. In general, it is important to avoid quickly closing valves in an HVAC system to minimize the occurrence of water hammer.

When flow stops, the pressure increase is independent of the working pressure of the system. For example, if water is flowing at 5 fps and a valve is instantly closed, the pressure increase is the same whether the normal pressure is 100 psig or 1000 psig.

Water hammer is often accompanied by a sound resembling a pipe being struck by a hammer—hence the name. The intensity of the sound is no measure of the magnitude of the pressure. Tests indicate that even if 15% of the shock pressure is removed by absorbers or arresters, adequate relief is not necessarily obtained.

Velocity of pressure wave and maximum water hammer pressure formulas may be found in the *Hydraulic Handbook* (Fairbanks Morse 1965).

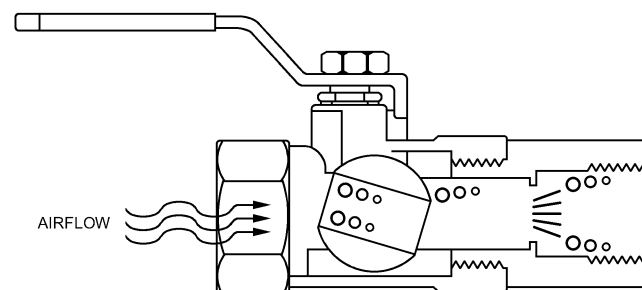
### Noise

Chapter 36 of the 2005 *ASHRAE Handbook—Fundamentals* points out that limitations are imposed on pipe size to control the level of pipe and valve noise, erosion, and water hammer pressure. One recommendation places a velocity limit of 4 fps for pipe 2 in. and smaller, and a pressure drop of 4 ft water/100 ft length for piping over 2 in. in diameter. Velocity-dependent noise in piping and piping systems results from any or all of four sources: turbulence, cavitation, release of entrained air, and water hammer (see Chapter 47 of the 2007 *ASHRAE Handbook—HVAC Applications*).

Some data are available for predicting hydrodynamic noise generated by control valves. ISA *Standard 75.01* compiled prediction correlations in an effort to develop control valves for reduced noise levels.

### Body Styles

Valve bodies are available in many configurations depending on the desired service. Usual functions include stopping flow, allowing



**Fig. 3** Valve Cavitation at Sharp Curves

full flow, modulating flow between extremes, and directing flow. The operation of a valve can be automatic or manual.

The shape of bodies for automatic and manual valves is dictated by the intended application. For example, angle valves are commonly provided for radiator control. The principle of flow is the same for angle and straight-through valve configurations; the manufacturer provides a choice in some cases as a convenience to the installer.

The type or design of body connections is dictated primarily by the proposed conduit or piping material. Depending on material type, valves can be attached to piping in one of the following ways:

- Bolted to the pipe with companion flange.
- Screwed to the pipe, where the pipe itself has matching threads (male) and the body of the valve has threads machined into it (female).
- Welded, soldered, or sweated.
- Flared, compression, and/or various mechanical connections to the pipe where there are no threads on the pipe or the body.
- Valves of various plastic materials are fastened to the pipe if the valve body and the pipe are of compatible plastics.

## MANUAL VALVES

### Selection

Each valve style has advantages and disadvantages for the application. In some cases, the design documents provide inadequate information, so that selection is based on economics and local stock availability by the installer and not on what is really required. Good submittal practice and approval by the designer are required to prevent substitutions. The questions listed in the section on Fundamentals must be evaluated carefully.

### Globe Valves

In a globe valve, flow is controlled by a circular disk forced against or withdrawn from an annular ring, or **seat**, that surrounds an opening through which flow occurs (Figure 4). The direction of movement of the disk is parallel to the direction of the flow through the valve opening (or seat) and normal to the axis of the pipe in which the valve is installed.

Globe valves are most frequently used in smaller diameter pipes but are available in sizes up to 12 in. They are used for throttling duty where positive shutoff is required. Globe valves for controlling service should be selected by class, and whether they are of the straight-through or angle type, composition disk, union or gasketed bonnet, threaded, and solder or grooved ends. Manually operated flow control valves are also available with fully guided V-port throttling plugs or needle point stems for precise adjustment.

### Gate Valves

A gate valve controls flow by means of a wedge disk fitting against machined seating faces (Figure 5). The straight-through opening of the valve is as large as the full bore of the pipe, and the gate movement is perpendicular to the flow path.

Gate valves are intended to be fully open or completely closed. They are designed to allow or stop flow, and should not be used to regulate or control flow. Various wedges for gate valves are available for specific applications. Valves in inaccessible locations may be provided with a chain wheel or with a hammer-blow operator. More detailed information is available from valve manufacturers.

### Plug Valves

A plug valve is a manual fluid flow control device (Figure 6). It operates from fully open to completely shut off within a 90° turn. The capacity of the valve depends on the ratio of the area of the orifice to the area of the pipe in which the valve is installed.

The cutaway view of a plug valve shows a valve with an orifice that is considerably smaller than the full size of the pipe. Lubricated plug valves are usually furnished in gas applications. A plug valve is selected as an on/off control device because (1) it is relatively inexpensive; (2) when adjusted, it holds its position; and (3) its position is clearly visible to the operator. The effectiveness of this valve as a flow control device is reduced if the orifice of the valve is fully ported (i.e., the same area as the pipe size).

### Ball Valves

A ball valve contains a precision ball held between two circular seals or seats. Ball valves have various port sizes. A 90° turn of the handle changes operation from fully open to fully closed. Ball valves for shutoff service may be fully ported. Ball valves for throttling or controlling and/or balancing service should have a reduced

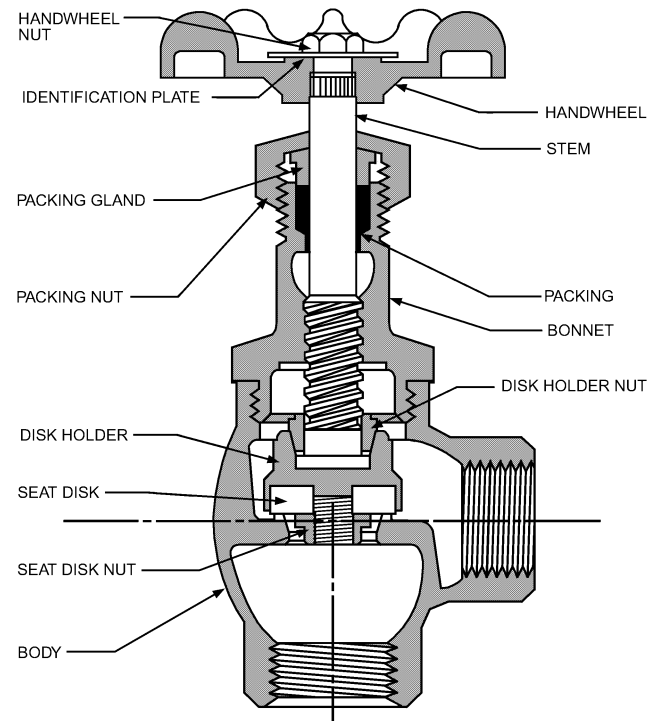


Fig. 4 Globe Valve  
(Courtesy Anvil Int'l.)

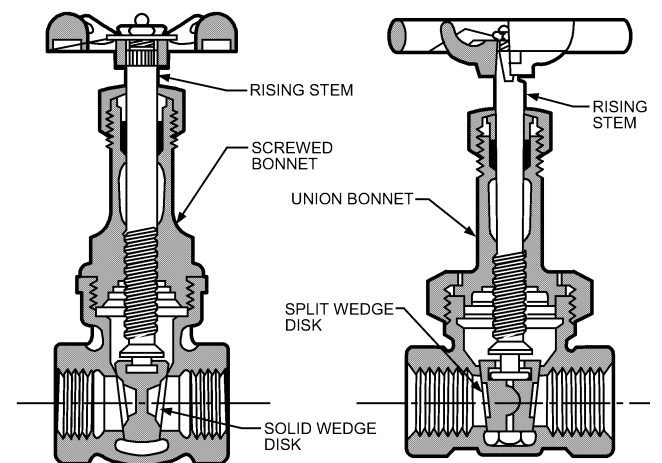


Fig. 5 Two Variations of Gate Valve

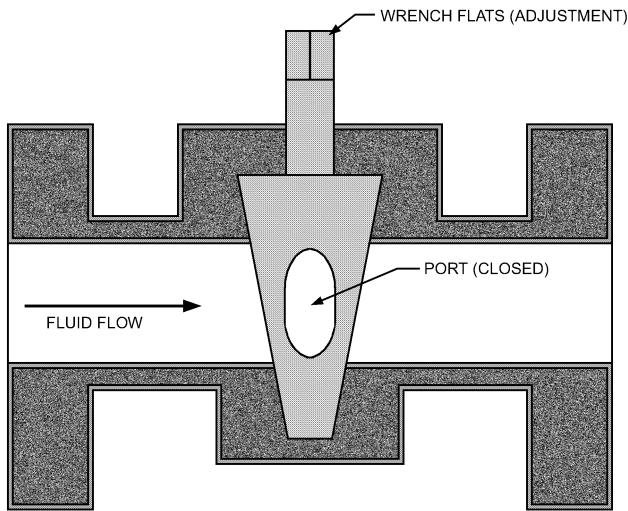


Fig. 6 Plug Valve

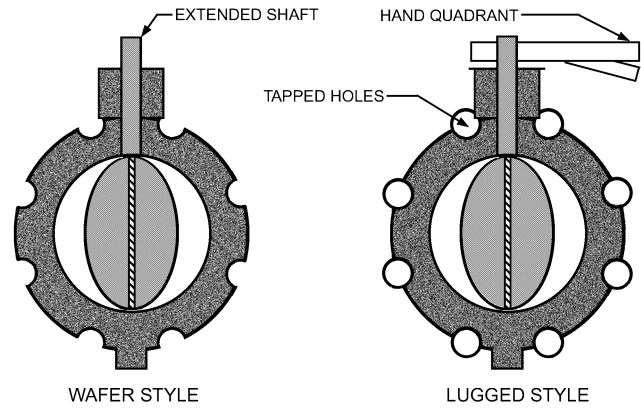


Fig. 8 Butterfly Valve

**style**, which is clamped between two companion flanges whose bolts carry the pipeline tensile stress and place the wafer body in compression, or **lugged style**, with tapped holes in the wafer body, which may serve as a future point of disconnection. The disk's axis of rotation is the valve stem; it is perpendicular to the flow path at the center of the valve body. Only a 90° turn of the valve disk is required to change from the full-open to the closed position. Butterfly valves may be manually operated with **hand quadrants** (levers) or provided with an extended shaft for automatic operation by an actuator. Special attention should be paid to manufacturers' recommendations for sizing an actuator to handle the torque requirements.

Simple and compact design, a low corresponding pressure drop, and fast operation characterize all butterfly valves. Quick operation makes them suitable for automated control, whereas the low pressure drop is suitable for high flow. Butterfly valve sizing for on/off applications should be limited to pipe sizing velocities given in Chapter 36 of the 2005 *ASHRAE Handbook—Fundamentals*; on the other hand, for throttling control applications, the valve coefficient sizing presented in the section on Automatic Valves must be followed.

**Pinch Valves**

Two styles of pinch valve bodies are normally used: the jacket pinch and the Saunders-type bodies used for slurry control in many industries. Pressure-squeezing the flexible tube jacket of a pinch valve reduces its port opening to control flow. The Saunders type uses an actuator to manually or automatically squeeze the diaphragm against a weir-type port. These valves have limited HVAC application.

**AUTOMATIC VALVES**

Automatic valves are commonly considered as control valves that operate in conjunction with an automatic controller or device to control the fluid flow. The "control valve" as used here actually consists of a valve body and an actuator. The valve body and actuator may be designed so that the actuator is removable and/or replaceable, or the actuator may be an integral part of the valve body. This section covers the most common types of valve actuators and control valves with the following classifications:

- Two-way bodies (single- and double-seated)
- Three-way bodies (mixing and diverting)
- Ball valves
- Butterfly arrangements (two- and three-way)

**Actuators**

The valve actuator converts the controller's output, such as an electric or pneumatic signal, into the rotary or linear action required

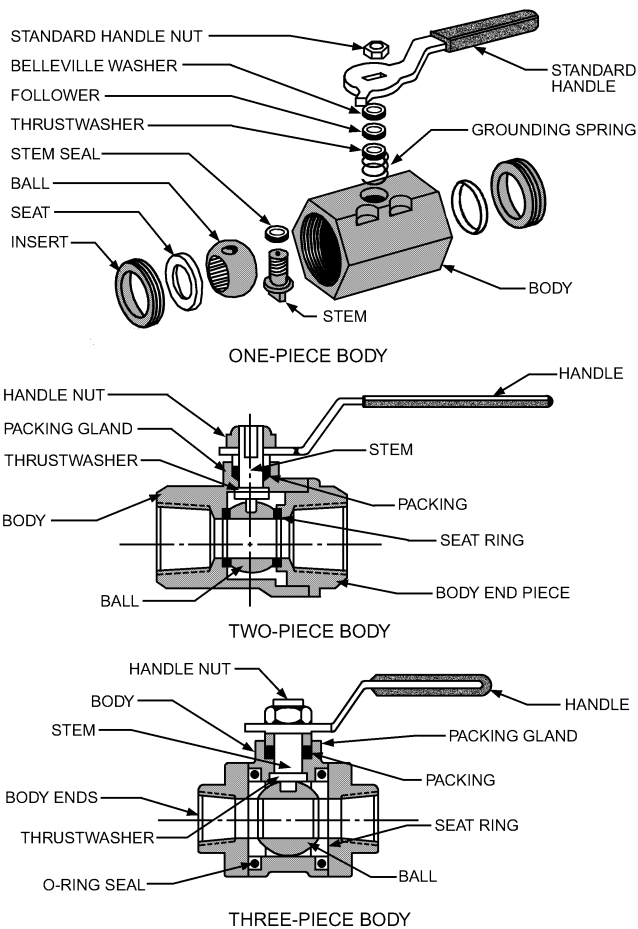


Fig. 7 Ball Valve

port with a plated ball and valve handle memory stop. Ball valves may be of one-, two-, or three-piece body design (Figure 7).

**Butterfly Valves**

A butterfly valve typically consists of a cylindrical, flanged-end body with an internal, rotatable disk serving as the fluid flow-regulating device (Figure 8). Butterfly valve bodies may be **wafer**

by the valve (stem), which changes the control variable (flow). Actuators cover a wide range of sizes, types, output capabilities, and control modes.

**Sizes.** Actuators range in physical size from small solenoid or clock motor self-operated types, to large pneumatic actuators with 100 to 200 in<sup>2</sup> of effective area.

**Types.** The most common types of actuators used on automatic valve applications are solenoid, thermostatic radiator, pneumatic, electric motor, electronic, and electrohydraulic.

**Output (Force) Capabilities.** Although the smallest actuators, designed for unitary commercial HVAC and residential control applications, are capable of only a very small output, larger pneumatic or electrohydraulic actuators are capable of great force. The overall force ranges from a few ounces to over 0.5 ton of force.

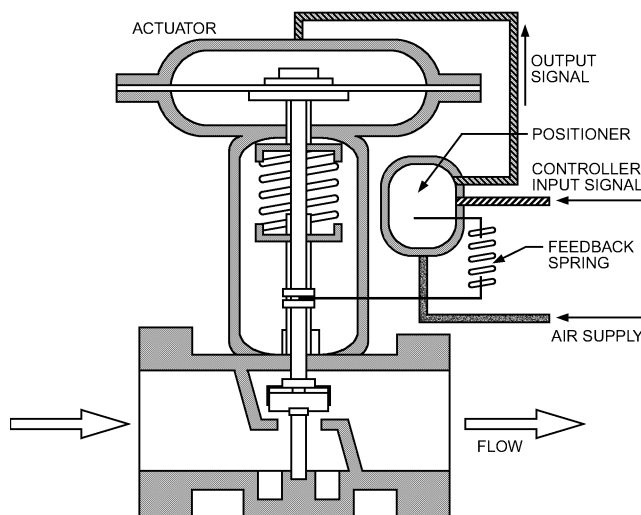
**Pneumatic Actuators**

Pneumatic or diaphragm valve actuators are available with diaphragm sizes ranging from 3 to 200 in<sup>2</sup>. The design consists of a flexible diaphragm clamped between an upper and a lower housing. On direct-acting actuators, the upper housing and diaphragm create a sealed chamber (Figure 9). A spring opposing the diaphragm force is positioned between the diaphragm and the lower housing. Increasing air pressure on the diaphragm pushes the valve stem down and overcomes the force of the load spring to close a direct-acting valve. Springs are designated by the air pressure change required to open or close the valve. A 5 lb spring requires a 5 psi control pressure change at the actuator to operate the valve. Some valves have an adjustable spring feature; others are fixed. Springs for commercial control valves usually have ±10% tolerance, so the 5 lb spring setting is 5 psi ± 0.5 psi. Two valves in a control may be sequenced simply with adjustable actuator springs.

Reverse-acting valves may use a direct-acting actuator if they have reverse-acting valve bodies; otherwise, the actuator must be reverse-acting and constructed with a sealed chamber between the lower housing and the diaphragm.

The valve close-off point shifts as the supply and/or the differential pressure increases across a single-seated valve because of the fixed areas of the actuator and the valve seat. The manufacturer's close-off rating tables need to be consulted to determine if the actuator is of an adequate size or if a larger actuator or a pneumatic positioner relay is required.

A **pneumatic positioner relay** may be added to the actuator to provide additional force to close or open an automatic control valve (Figure 9). Sometimes called positive positioners or pilot positioners,



**Fig. 9 Two-Way, Direct-Acting Control Valve with Pneumatic Actuator and Positioner**

pneumatic positioners are basically high-capacity relays that add air pressure to or exhaust air pressure from the actuator in relation to the stroke position of the actuator. Their application is limited by the supply air pressure available and by the actuator's spring.

**Electric Actuators**

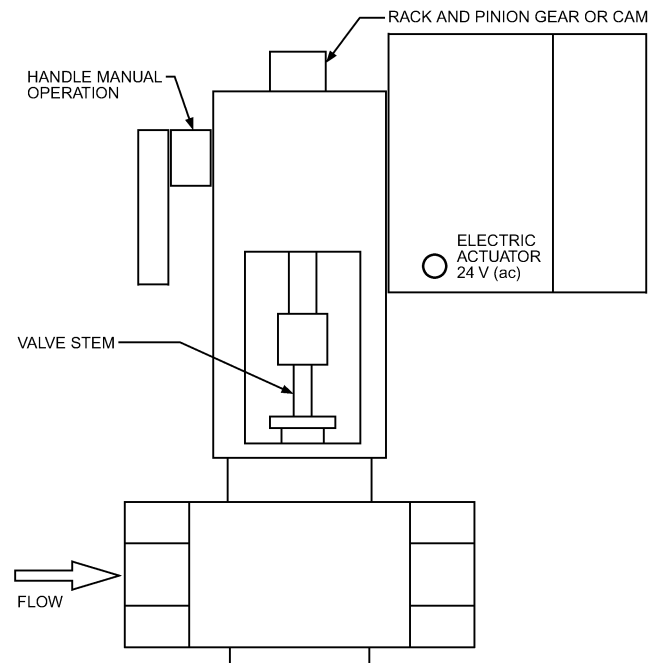
Electric actuators usually consist of a double-wound electric motor coupled to a gear train and an output shaft connected to the valve stem with a cam or rack-and-pinion gear linkage (Figure 10). For valve actuation, the motor shaft typically drives through 160° of rotation. The use of damper actuators with 90° full stroke rotation is rapidly increasing in valve control applications. Gear trains are coupled internally to the electric actuators to provide a timed movement of valve stroke to increase operating torque and to reduce overshooting of valve movement. Gear trains can be fitted with limit switches, auxiliary potentiometers, etc., to provide position indication and feedback for additional system control functions.

In many instances, a linkage is required to convert rotary motion to the linear motion required to operate a control valve (except ball and butterfly valves). Electric valve actuators operate with two-position, floating, proportional electric, and electronic control systems. Actuators usually operate with a 24 V (ac) low-voltage control circuit. Actuator time to rotate (or drive full stroke) ranges from 30 s to 4 min, with 60 s being most common.

Electric valve actuators may have a spring return, which returns the valve to a normal position in case of power failure, or it may be powered with an electric relay and auxiliary power source. Because the motor must constantly drive in one direction against the return spring, spring return electric valve actuators generally have only approximately one-third of the torque output of non-spring return actuators.

**Electrohydraulic Actuators**

Hydraulic actuators combine characteristics of electric and pneumatic actuators. In essence, hydraulic actuators consist of a sealed housing containing the hydraulic fluid, pump, and some type of metering or control apparatus to provide pressure control across a piston or piston/diaphragm. A coil controlled by a low- to medium-level dc voltage usually activates the pressure control apparatus.



**Fig. 10 Two-Way Control Valve with Electric Actuator**

**Solenoids**

A solenoid valve is an electromechanical control element that opens or closes a valve on the energization of a solenoid coil. Solenoid valves are used to control the flow of hot or chilled water and steam and range in size from 1/8 to 2 in. pipe size. Solenoid actuators themselves are two-position control devices and are available for operation in a wide range of alternating current voltages (both 50 and 60 Hz) as well as direct current. Operation of a simple two-way, direct-acting solenoid valve in a deenergized state is illustrated in [Figure 11](#).

**Thermostatic Radiator Valves**

Thermostatic radiator valves are self-operated and do not require external energy. They control room or space temperature by modulating the flow of hot water or steam through free-standing radiators, convectors, or baseboard heating units. Thermostatic radiator valves are available for a variety of installation requirements with remote-mounted sensors or integral-mounted sensor and remote or integral set point adjustment ([Figure 12](#)).

**Control of Automatic Valves**

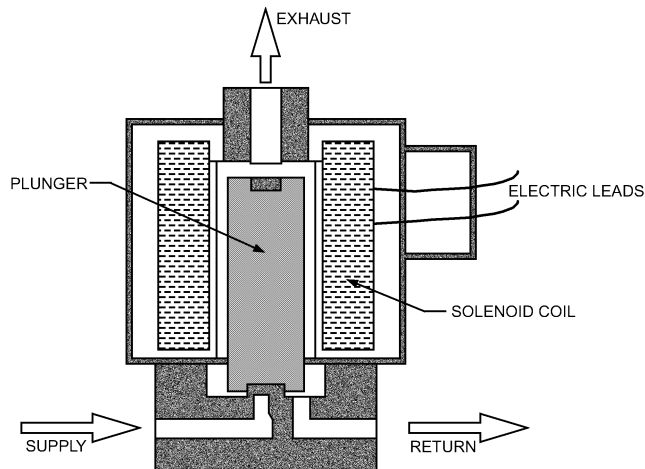
Computer-based control of automatic control valves is replacing older technologies and provides many benefits, including speed, accuracy, and data communication. However, care must be used in selecting the value of control loop parameters such as loop speed and dead band (allowable set-point deviation). High loop speed coupled with zero dead band can cause the valve-actuator to seek a new control position with each control loop cycle unless the actuator itself has some type of built-in protection against this. For example, a 1 s control loop with zero dead band could result in 30,000,000 repositions (corrections) in 1 year of service.

Computer-based control systems should be tuned to provide the minimum acceptable level of response and accuracy required for the application in order to achieve maximum valve and actuator service life.

**Two-Way Valves (Single- and Double-Seated)**

In a two-way automatic valve, the fluid enters the inlet port and exits the outlet port either at full or reduced volume, depending on the position of the stem and the disk in the valve. Two-way valves may be single- or double-seated.

In the single-seated valve, one seat and one plug-disk close against the stream. The style of the plug-disk varies depending on the requirements of the designer and the application. For body comparison, refer to Figure 8 in Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals*.



**Fig. 11 Electric Solenoid Valve**

The double-seated valve is a special application of the two-way valve with two seats, plugs, and disks. It is generally applied to cases where the close-off pressure is too high for the single-seated valve.

**Three-Way Valves**

Three-way valves either mix or divert streams of fluid. [Figure 13](#) shows some common applications for three-way valves. Figure 9 in Chapter 15 of the 2005 *ASHRAE Handbook—Fundamentals* shows typical cross sections of three-way mixing and diverting valves.

The **three-way mixing valve** blends two streams into one common stream based on the position of the valve plug in relation to the upper and lower seats of the valve. A common use is to mix chilled or hot water. The valve controls the temperature of the single stream leaving the valve.

The **three-way diverting or bypass valve** takes one stream of fluid and splits it into two streams for temperature control. In some limited applications, such as a cooling tower control, a diverting or bypass valve must be used in place of a mixing valve. In most cases, a mixing valve can perform the same function as a diverting or bypass valve if the companion actuator has a very high spring rate. Otherwise, water hammer or noise may occur when operating near the seat.

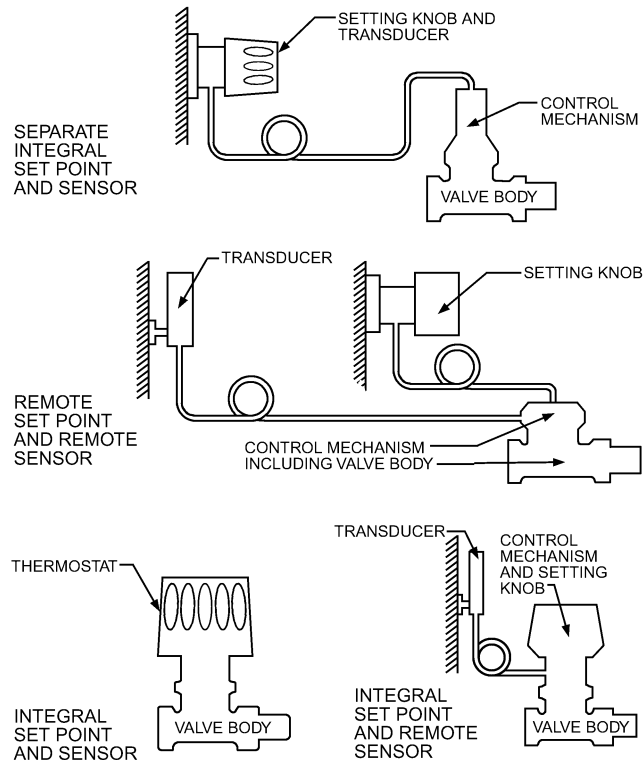
**Special-Purpose Valves**

Special-purpose valve bodies may be used on occasion. One type of four-way valve is used to allow separate circulation in the boiler loop and a heated zone. Another type of four-way valve body is used as a changeover refrigeration valve in heat pump systems to reverse the evaporator to a condenser function.

Float valves are used to supply water to a tank or reservoir or serve as a boiler feed valve to maintain an operating water level at the float level location ([Figure 14](#)).

**Ball Valves**

Ball valves coupled with rotary actuators have seen increasing use in HVAC control applications. A reduced port should be used on

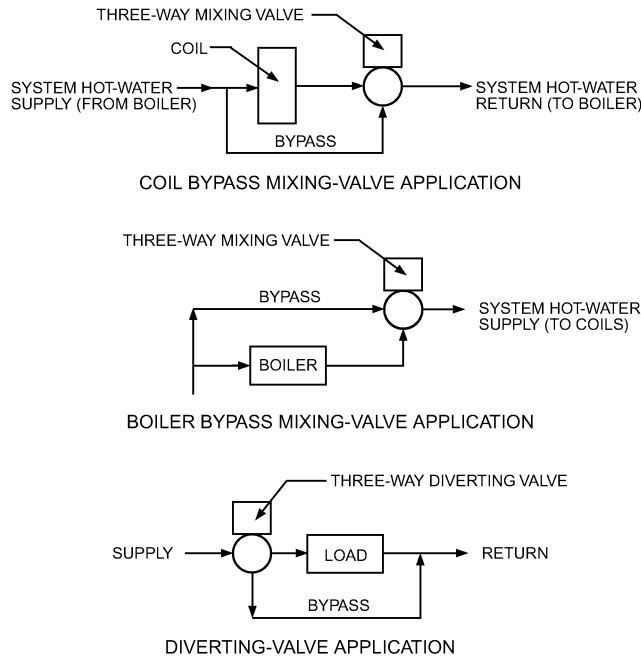


**Fig. 12 Thermostatic Valves**

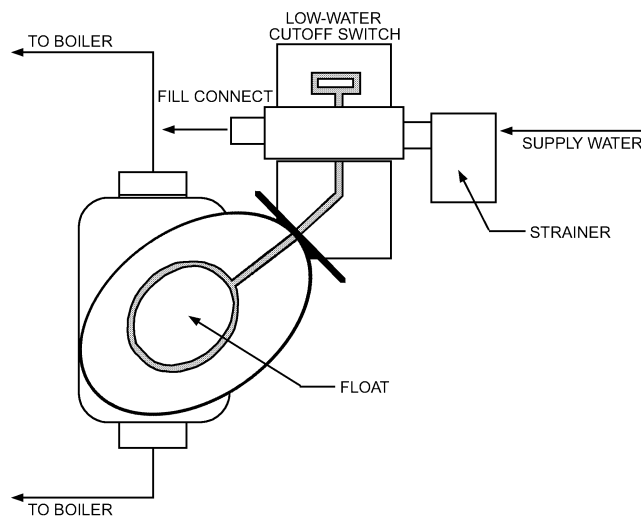
the ball valve, or the valve should be sized smaller than the piping system to achieve adequate control (pressure drop). In some cases, the packing system of ball valves has been redesigned to accommodate the modulating control action inherent in HVAC. The control characteristic for full-ported ball valves is equal percentage, but modified seats, ball ports, or inserts are available to provide other characteristics (e.g., linear, modified linear, etc.).

**Butterfly Valves**

In some applications, it is not possible to use standard three-way mixing or bypass valves because of size limitations or space constraints. In these cases, two butterfly valves are mounted on a piping tee and cross-linked to operate as either three-way mixing or three-way bypass valves (Figure 15). Butterfly valves have different flow characteristics from standard seat and disk-type valves, so they may be used only where their flow characteristics suffice.



**Fig. 13 Typical Three-Way Control Applications**

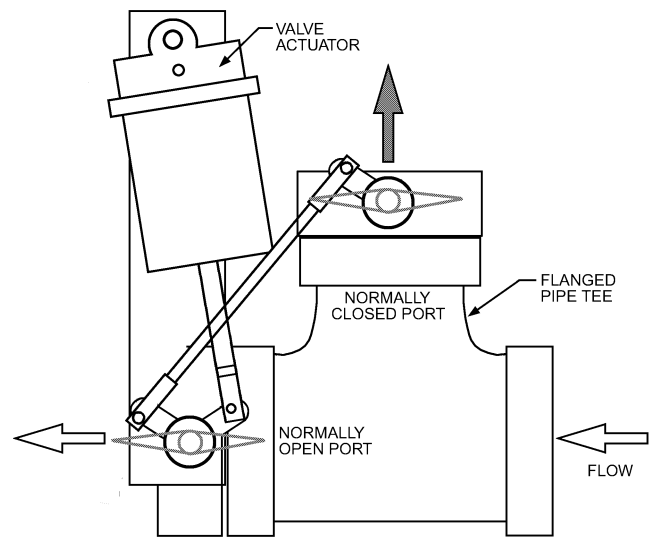


**Fig. 14 Float Valve and Cutoff Steam Boiler Application**

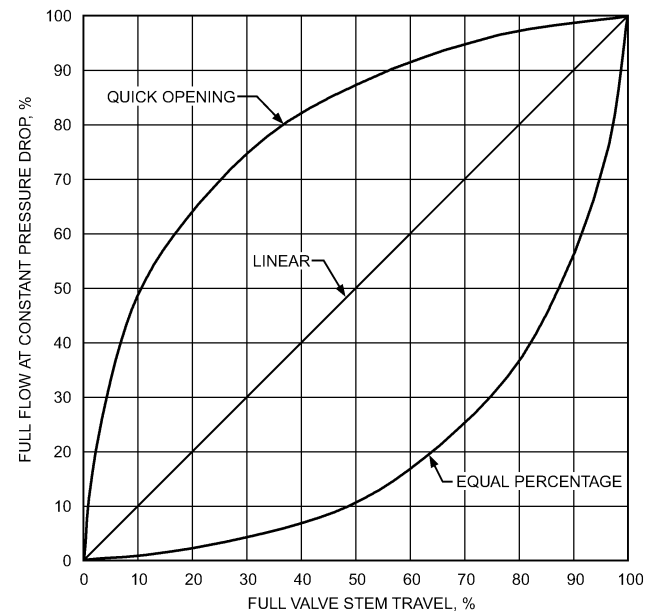
**Control Valve Flow Characteristics**

Generally, valves control the flow of fluids by an actuator, which moves a stem with an attached plug. The plug seats within the valve port and against the valve seat with a composition disk or metal-to-metal seating. Based on the geometry of the plug, three distinct flow conditions can be developed (Figure 16):

- **Quick Opening.** When started from the closed position, a quick-opening valve allows a considerable amount of flow to pass for small stem travel. As the stem moves toward the open position, the rate at which the flow is increased per movement of the stem is reduced in a nonlinear fashion. This characteristic is used in two-position or on/off applications.
- **Linear.** Linear valves produce equal flow increments per equal stem travel throughout the travel range of the stem. This characteristic is used on steam coil terminals and in the bypass port of three-way valves.



**Fig. 15 Butterfly Valves, Diverting Tee Application**



**Fig. 16 Control Valve Flow Characteristics**

• **Equal Percentage.** This type of valve produces an exponential flow increase as the stem moves from the closed position to the open. The term equal percentage means that for equal increments of stem travel, the flow increases by an equal percentage. For example, in Figure 16, if the valve is moved from 50 to 70% of full stroke, the percentage of full flow changes from 10 to 25%, an increase of 150%. Then, if the valve is moved from 80 to 100% of full stroke, the percentage of full flow changes from 40 to 100%, again, an increase of 150%. This characteristic is recommended for control on hot and chilled water terminals.

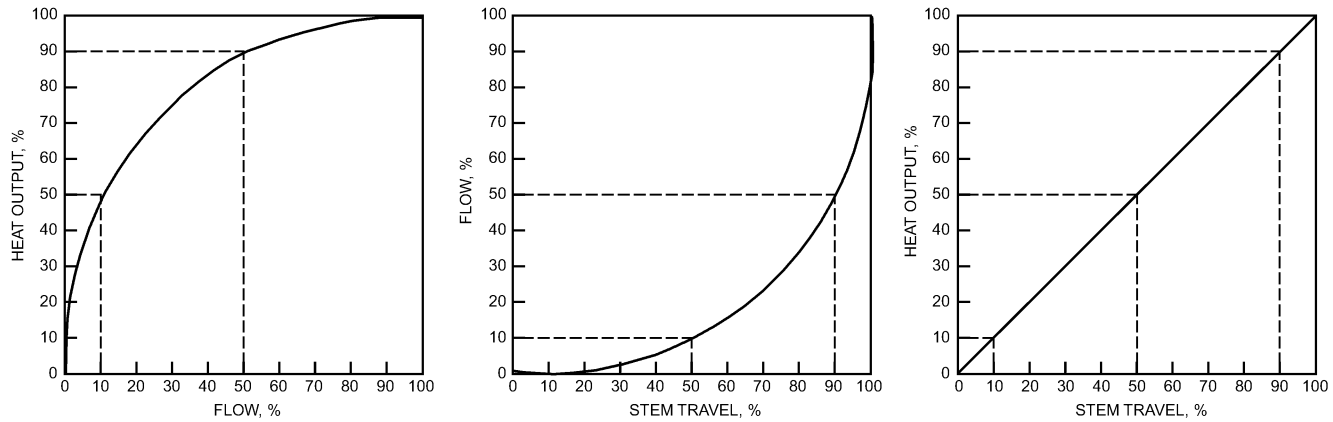
Control valves are commonly used in combination with a coil and another valve within a circuit to be controlled. The designer should combine the valve flow characteristics with coil performance curves (heating or cooling) because the resulting energy output profile of the circuit versus the stem travel improves (Figure 17). For a typical hydronic heating or cooling coil, the equal percentage results in the closest to a linear change and provides the most efficient control (Figure 17).

The three flow patterns are obtained by imposing a constant pressure drop across the modulating valve, but in actual conditions, the pressure drop across the valve varies between a maximum (when it

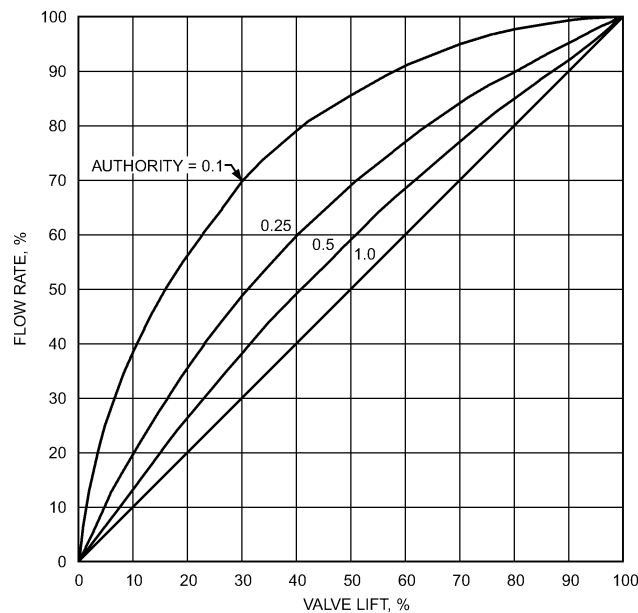
is controlling) and a minimum (when the valve is near full open). The ratio of these two pressure drops is known as **authority**. Figures 18 and 19 show how linear and equal-percentage valve flow characteristic are distorted as the control valve authority is reduced because of a reduction in valve pressure drop. The quick-opening characteristic, not shown, is distorted to the point that it approaches two-position or on/off control. The selection of the control valve pressure drop directly affects the valve authority and should be at least 25 to 50% of the system loop pressure drop (i.e., the pressure drop from the pump discharge flange, supply main, supply riser, supply branch, heat transfer coil, return branch, fittings, balancing valve, and return main to the pump suction flange). The location of the control valve in the system results in unique pressure drop selections for each control valve. A higher valve pressure drop allows a smaller valve pipe size and better control.

**Control Valve Sizing**

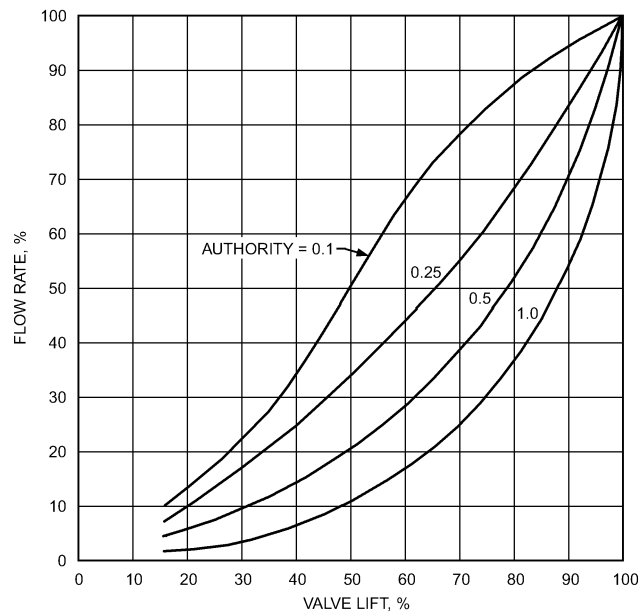
**Liquids.** A valve creates fluid resistance in a circuit to limit the flow of the fluid at a calculated pressure drop. Each passive element in a circuit creates a pressure drop according to the following general equation:



**Fig. 17 Heat Output, Flow, and Stem Travel Characteristics of Equal Percentage Valve**



**Fig. 18 Authority Distortion of Linear Flow Characteristics**



**Fig. 19 Authority Distortion of Equal-Percentage Flow Characteristic**

$$\Delta p = RQ^n \left( \frac{\rho}{\rho_w} \right) \quad (1)$$

where

- $\Delta p$  = pressure drop, psi
- $R$  = resistance
- $\rho$  = fluid density, lb/ft<sup>3</sup>
- $\rho_w$  = density of water at 60°F, lb/ft<sup>3</sup>
- $Q$  = volumetric flow, gpm
- $n$  = system coefficient

For turbulent flows,  $n$  is assumed to be 2, although for steel pipes  $n = 1.85$ .

For a valve, assuming  $n = 2$ , Equation (1) can be solved for flow:

$$Q = \sqrt{\left( \frac{\Delta p}{R} \right) \left( \frac{\rho_w}{\rho} \right)} \quad (2)$$

The term  $\sqrt{1/R}$  can be replaced by the flow coefficient  $C_v$ , the ratio  $\rho/\rho_w$  is approximately 1 for water at temperatures below 250°F, and Equation (2) becomes

$$Q = C_v \sqrt{\Delta p} \quad (3)$$

or

$$Q = 0.67 C_v \sqrt{\Delta h} \quad (4)$$

where  $\Delta h$  = pressure drop, ft of water.

The control valve size should be selected by calculating the required  $C_v$  to provide the design flow at an assumed pressure drop  $\Delta p$ . A pressure drop of 25 to 50% of the available pressure between the supply and return riser (pump head) should be selected for the control valve. This pressure drop gives the best flow characteristic as described in the section on Control Valve Flow Characteristics.

For liquids with a viscosity correction factor  $V_f$ ,

$$Q = \frac{C_v}{V_f} \sqrt{\Delta p \left( \frac{\rho_w}{\rho} \right)} \quad (5)$$

**Steam.** For steam flow,

$$w_s = 2.1 \frac{C_v}{K} \sqrt{\Delta p (P_1 + P_2)} \quad (6)$$

where

- $w_s$  = steam flow, lb/h
- $K = 1 + 0.0007 \times (\text{°F of superheat})$
- $C_v$  = flow coefficient, gpm at  $\Delta p = 1$  psi
- $P_1$  = entering steam absolute pressure
- $P_2$  = leaving steam absolute pressure
- $\Delta p$  = steam pressure drop across valve,  $P_1 - P_2$

*Note:* Some manufacturers list the constant in Equation (6) as high as 3.2, but most agree on 2.1. As part of good practice, always confirm valve sizing with the manufacturer.

Steam reaches critical or sonic velocity when the downstream pressure is 58% or less of the absolute inlet pressure. If the downstream pressure is below the critical pressure, increasing the pressure drop produces no further increase in flow. As a result, when  $P_2 \leq 0.58P_1$ , the following critical pressure drop formula is used:

$$C_v = \frac{w_s}{1.61 P_1} \quad (7)$$

## Applications

Automatically controlled valves are applied to control many different variables, the most common being temperature, humidity, flow, and pressure. However, a valve can be used directly to control

only flow or pressure. When flow is controlled, a pressure drop is implied, and when pressure is controlled, some maximum flow rate is implied. These two factors must be considered in selecting control valves. For some typical valve applications, refer to Chapter 46 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Although the discussion in this chapter applies to hot water, chilled water, and steam, control valves can be used with virtually any fluid. The fluid characteristics must be considered in selecting materials for the valve. The requirements are particularly strict for use with high-temperature water and high-pressure steam.

Steam is controlled in two ways:

1. When steam pressure is too high for use in a specific application, the pressure must be reduced by a **pressure-reducing valve** (PRV). This is normally a globe-type valve, because modulating control is required. The valve may be externally or internally piloted and is usually self-contained, using the steam pressure to drive the actuator. The load may vary, so it is sometimes desirable to use two or more valves in parallel, adjusted to open in sequence, for more accurate control.
2. Steam flow to a heat exchanger may be controlled in response to temperature or humidity requirements. In this case, an external control system is used with the steam valve as the controlled device. In selecting a steam valve, the maximum flow rate for the specific valve and entering steam pressure must be considered. These factors are determined from the critical pressure drop, which limits the flow.

Hot and chilled water are usually controlled in response to temperature or humidity requirements. When selecting a valve for controlling water flow, a pressure drop sufficiently large to allow the valve to control properly should be specified. The response of the heat exchanger coil to a change in flow is not linear; therefore, an equal-percentage plug should be used, and the temperature of the water supply should be as high (hot water) or as low (chilled water) as required by the load conditions.

## BALANCING VALVES

Two approaches are available for balancing hydronic systems: (1) a manual valve with integral pressure taps and a calibrated port, which allows field proportional balancing to the design flow conditions; (2) or an automatic flow-limiting valve selected to limit the circuit's maximum flow to the design flow.

### Manual Balancing Valves

Manual balancing valves can be provided with the following features:

- Manually adjustable stems for valve port opening or a combination of a venturi or orifice and an adjustable valve
- Stem indicator and/or scale to indicate the relative amount of valve opening
- Pressure taps to provide a readout of the pressure difference across the valve port or the venturi/orifice
- Capability to be used as a shutoff for future service of the heat transfer terminal
- Locking device for field setting the maximum opening of a valve
- Body tapped for attaching drain hose

Manual balancing valves may have rotary, rising, or nonrising stems for port adjustment ([Figure 20](#)).

Meters with various scale ranges, a field carrying case, attachment hoses, and fittings for connecting to the manual balancing valve should be used to determine its flow by reading the differential pressure. Some meters use analog measuring elements with direct-reading mechanical dual-element Bourdon tubes. Other meters are electronic differential pressure transducers with a digital data display.

Many manufacturers of balancing valves produce circular slide rules to calculate circuit flow based on pressure difference readout across the balancing valve, its stem position, and/or the valve's flow coefficient. This calculator can also be used for selecting the size and setting of the valve when the terminal design flow conditions are known.

**Automatic Flow-Limiting Valves**

A differential pressure-actuated flow control valve, also called an automatic flow-limiting valve (Figure 21), regulates the flow of fluid to a preset value when the differential pressure across it is varied. This regulation (1) helps prevent an overflow condition in the circuit where it is installed and (2) aids the overall system balance when other components are changing (modulating valves, pump staging, etc.).

Typically, the valve body contains a moving element containing an orifice, which adjusts itself based on pressure forces so that the flow passage area varies.

The area of an orifice can be changed by either (1) a piston or cup moving across a shear plate or (2) increased pressure drop to squeeze the rubber orifice in rubber grommet valves.

A typical performance curve for the valve is shown in Figure 22. The flow rate for the valve is set. The flow curve is divided into three ranges of differential pressure: the start-up range, the control range, and the above-control range.

**Balancing Valve Selection**

The balancing valve is a flow control device that is selected for a lower pressure drop than an automatic control valve (5 to 10% of the available system pressure). Selection of any control valve is based on the pressure drop at maximum (design) flow to ensure that the valve provides control at all flow rates. A properly selected balancing valve can proportionally balance flow to its terminal with flow to the adjacent terminal in the same distribution zone. Refer to Chapter 37 of the 2007 ASHRAE Handbook—HVAC Applications for balancing details.

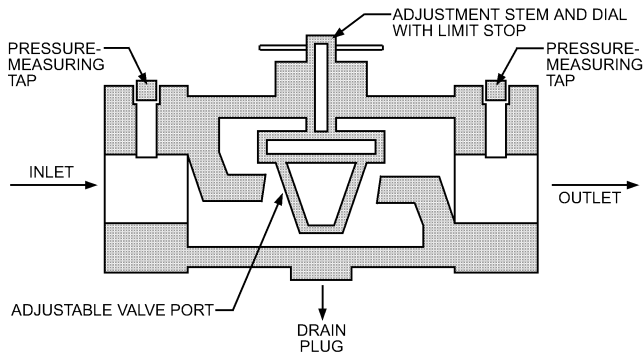


Fig. 20 Manual Balancing Valve

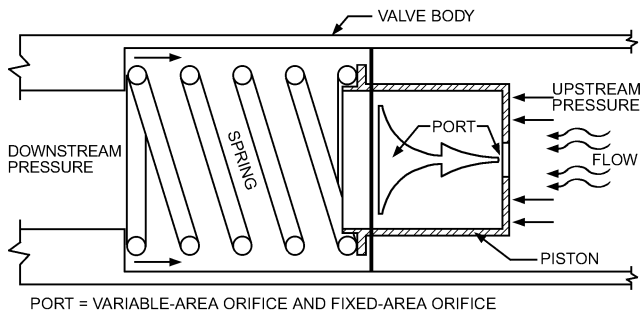


Fig. 21 Automatic Flow-Limiting Valve

**MULTIPLE-PURPOSE VALVES**

Multiple-purpose valves are made in straight pattern or angle pattern. The valves can provide shutoff for servicing or can be partially closed for balancing. Pressure gage connections to read the pressure drop across the valve can be used with the manufacturer's calibration chart or meter to estimate the flow. Means are provided to return the valve to its as-balanced position after shutoff for servicing. The valve also acts as a check valve to prevent backflow when parallel pumps are used and one of the pumps is cycled off.

Figure 23 shows a straight pattern multiple-purpose valve designed to be installed 5 to 10 pipe diameters from the pump discharge of a hydronic system.

Figure 24 shows an angle pattern multiple-purpose valve installed 5 to 10 pipe diameters downstream of the pump discharge with a common gage and a push button trumpet valve manifold to measure the differential pressure across the strainer, pump, or multiple-purpose valve. From this, the flow can be estimated. The differential pressure across the pump suction strainer can also be estimated to determine whether the strainer needs servicing.

**SAFETY DEVICES**

The terms safety valve, relief valve, and safety relief valve are sometimes used interchangeably, and although the devices generally provide a similar function (safety), they have important differences in their modes of operation and application in HVAC systems (Jordan 1998).

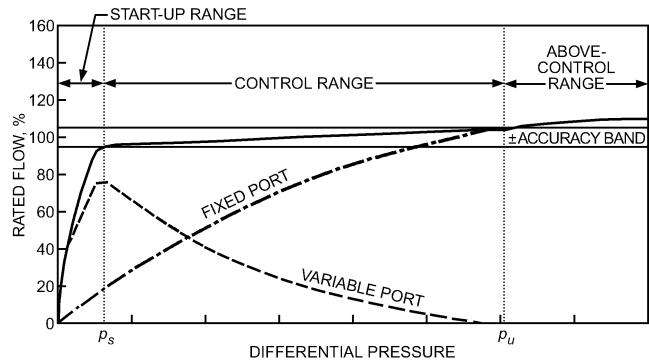


Fig. 22 Automatic Flow-Limiting Valve Curve

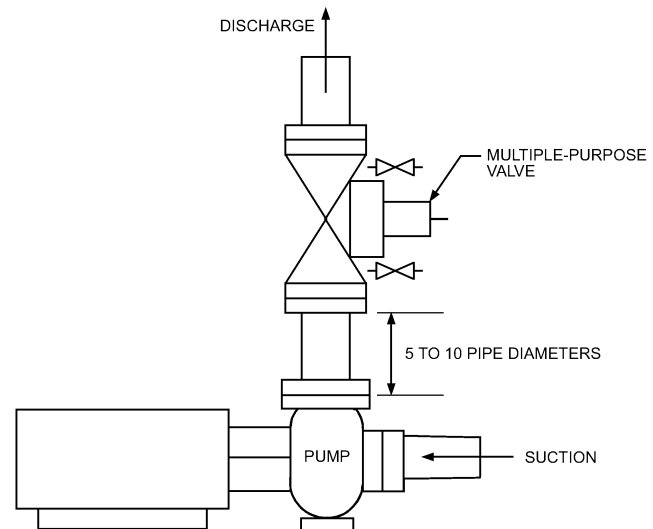


Fig. 23 Typical Multiple-Purpose Valve (Straight Pattern) on Discharge of Pump

**Safety valves** open rapidly (pop-action). They are used for gases and vapors (e.g., compressed air and steam).

**Relief valves** open or close gradually in proportion to excessive pressure. They are used for liquids (e.g., unheated water).

**Safety relief valves** perform a dual function: they open rapidly (pop-action) for gases and vapors and gradually for liquids. Typical HVAC application is for heating water.

**Temperature-actuated pressure relief valves** (or temperature and pressure safety relief valves) are activated by excessive temperature or pressure. They are commonly used for potable hot water.

Application of these safety devices must comply with building codes and the ASME *Boiler and Pressure Vessel Code*. For the remainder of this discussion, the term “safety valve” is used generically to include any or all of the four types described.

Safety valve construction, capacities, limitations, operation, and repair are covered by the ASME *Boiler and Pressure Vessel Code*. For pressures above 15 psig, refer to Section I. Section IV covers steam boilers for pressures less than 15 psig. Unfired pressure vessels (such as heat exchange process equipment or pressure-reducing valves) are covered by Section VIII.

The capacity of a safety valve is affected by the equipment on which it is installed and the applicable code. Valves are chosen based on accumulation, which is the pressure increase above the maximum allowable working pressure of the vessel during valve discharge. Section I valves are based on 3% accumulation. Accumulation may be as high as 33.3% for Section IV valves and 10% for Section VIII. To properly size a safety valve, the required capacity and set pressure must be known. On a pressure-reducing valve station, the safety valve must have sufficient capacity to prevent an unsafe pressure rise if the reducing valve fails in the open position.

The safety valve set pressure should be high enough to allow the valve to remain closed during normal operation, yet allow it to open and reseal tightly when cycling. A minimum differential of 5 psi or 10% of inlet pressure (whichever is greater) is recommended.

When installing a safety valve, consider the following:

- Install the valve vertically with the drain holes open or piped to drain.
- The seat can be distorted if the valve is overtight or the weight of the discharge piping is carried by the valve body. A drip-pan elbow on the discharge of the safety valve prevents the weight of the discharge piping from resting on the valve (Figure 25).
- Use a moderate amount of pipe thread lubricant (first 2 to 3 threads) on male threads.
- Install clean flange connections with new gaskets, properly aligned and parallel, and bolted with even torque to prevent distortion.
- Wire cable or chain pulls attached to the test levers should allow for a vertical pull, and their weight should not be carried by the valve.

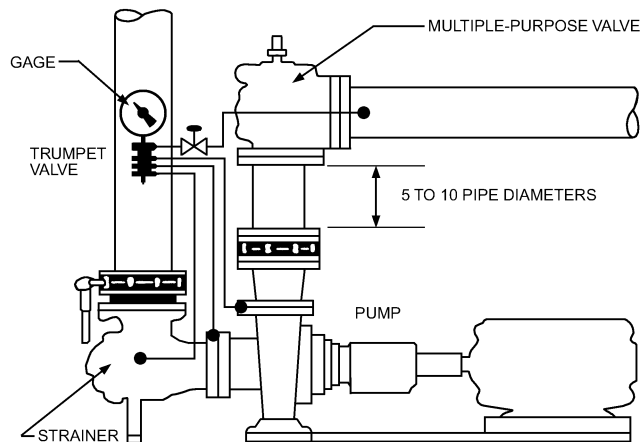


Fig. 24 Typical Multiple-Purpose Valve (Angle Pattern) on Discharge of Pump

Testing of safety valves varies between facilities depending on operating conditions. Under normal conditions, safety valves with a working pressure under 400 psig should be tested manually once per month and pressure-tested once each year. For higher pressures, the test frequency should be based on operating experience.

When steam safety valves require repair, adjustment, or set pressure change, the manufacturer or approved stations holding the ASME V, UV, and/or VR stamps must perform the work. Only the manufacturer is allowed to repair Section IV valves.

### SELF-CONTAINED TEMPERATURE CONTROL VALVES

Self-contained or self-operated temperature control valves do not require an outside energy source such as compressed air or electricity (Figure 26). They depend on a temperature-sensing bulb and

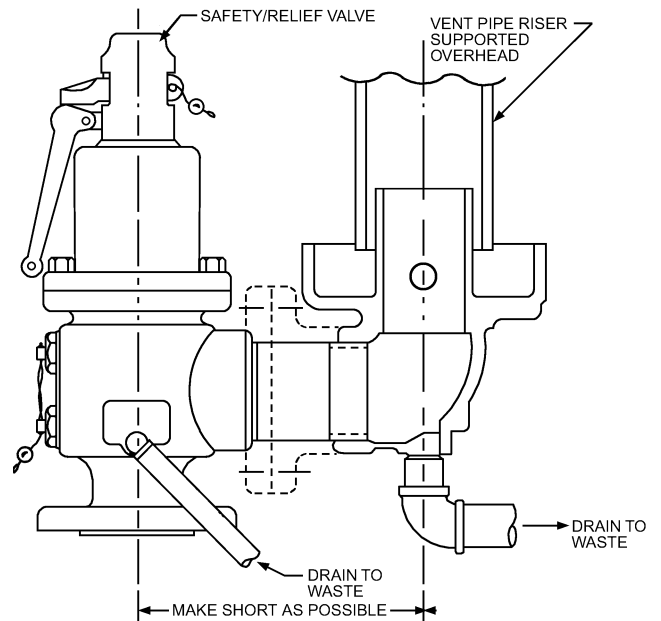


Fig. 25 Safety/Relief Valve with Drip-Pan Elbow

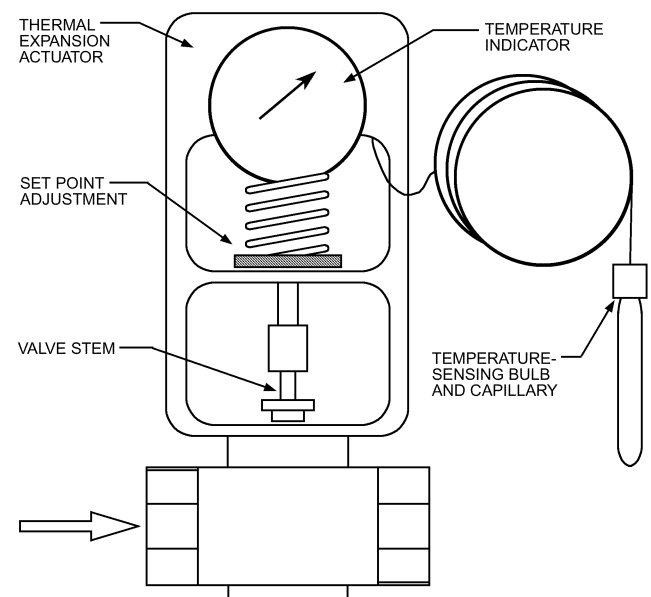


Fig. 26 Self-Operated Temperature Control Valve

capillary tube filled with either an oil or a volatile liquid. In an **oil-filled** system, the oil expands as the sensing bulb is heated. This expansion is transmitted through the capillary tube to an actuator bellows in the valve top, which causes the valve to close. The valve opens as the sensing bulb cools and the oil contracts; a spring provides a return force on the valve stem.

A volatile-liquid control system is known as a **vapor pressure** or **vapor tension** system. When the sensing bulb is warmed, some of the volatile liquid vaporizes, causing an increase in the sealed system pressure. The pressure rise is transmitted through the capillary tube to expand the bellows, which then moves the valve stem and closes the valve. Thermal systems actuate the control valve either directly or through a pilot valve.

In a **direct-actuated** design, the control directly moves the valve stem and plug to close or open the valve. These valves must compensate for the steam pressure force acting on the valve seat by generating a greater force in the bellows to close the valve. An adjustable spring adjusts the temperature set point and provides the return force to move the valve stem upward as the temperature decreases.

A **pilot-operated valve** (Figure 27) uses a much smaller intermediate pilot valve that controls the flow of steam to a large diaphragm that then acts on the valve stem. This allows the control system to work against high steam pressures caused by the smaller area of the pilot valve.

For self-contained temperature valves to operate as proportional controls, the bulb must sense a change in the temperature of the process fluid. The difference in temperature from no-load to maximum controllable load is known as the **proportional band**. Because the size of this proportional band can be varied depending on valve size, the accuracy is variable. Depending on the application, proportional bands of 2 to 18°F may be selected, as shown in the following table:

Application	Proportional Band, °F
Domestic hot-water heat exchanger	6 to 14
Central hot water	4 to 7
Space heating	2 to 5
Bulk storage	4 to 18

Although their response time, accuracy, and ease of adjustment may not be as good as those of electrically or pneumatically actuated valves, self-contained steam temperature controls are widely accepted for many applications.

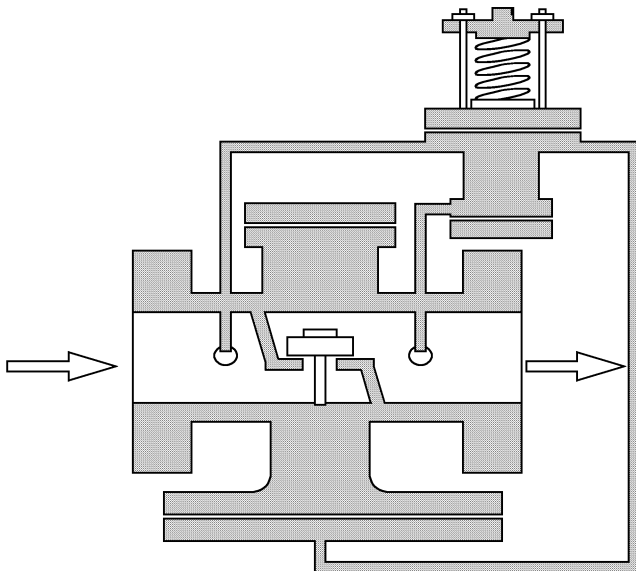


Fig. 27 Pilot-Operated Steam Valve

## PRESSURE-REDUCING VALVES

Should steam pressure be too high for a specific process, a self-contained pressure-reducing valve (PRV) may be used to reduce this pressure, which will also increase the available latent heat. These valves may be direct-acting or pilot-operated (Figure 27), much like temperature control valves. To maintain set pressure, the downstream pressure must be sensed either through an internal port or an external line.

The amount of pressure drop below the set pressure that causes the valve to react to a load change is called **droop**. As a general rule, pilot-operated valves have less droop than direct-acting types. To properly size these valves, only the mass flow of steam, the inlet pressure, and the required outlet pressure must be known. Valve line size can be determined by consulting manufacturers' capacity charts.

Because of their construction, simplicity, accuracy, and ease of installation and maintenance, these valves have been specified for most steam-reducing stations.

## Makeup Water Valves

A pressure-reducing valve is normally provided on a hydronic heating or cooling system to automatically fill the system with domestic or city water to maintain a minimum system pressure. This valve may be referred to as a fill valve, PRV fill valve, or automatic PRV makeup water valve, and is usually located at or near the system expansion tank. Local plumbing codes may require a backflow prevention device where the city water connects to the building domestic water system (see the section on Backflow Prevention Devices).

## CHECK VALVES

Check valves prevent reversal of flow, controlling the direction of flow rather than stopping or starting flow. Some basic types include swing check, ball check, wafer check, silent check, and stop-check valves. Most check valves are available in screwed and flanged body styles.

**Swing check valves** have hinge-mounted disks that open and close with flow (Figure 28). The seats are generally made of metal, whereas the disks may be of metallic or nonmetallic composition materials. Nonmetallic disks are recommended for fluids containing dirt particles or where tighter shutoff is required. The Y-pattern check valve has an access opening to allow cleaning and regrinding in place. Pressure drop through swing check valves is lower than that through lift check valves because of the straight-through design. Weight- or spring-loaded lever arm check valves are available to limit objectionable slamming or chattering when pulsating flows are encountered.

**Lift check valves** have a body similar in design to a globe or angle valve body with a similar disk seating. The guided valve disk is forced open by the flow and closes when flow reverses. Because of the body design, the pressure drop is higher than that of a swing check valve. Lift check valves are recommended for gas or compressed air or in fluid systems not having critical pressure drops.

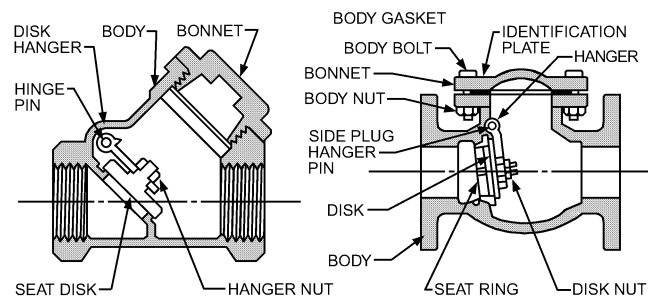


Fig. 28 Swing Check Valves  
(Courtesy Anvil Int'l.)

**Ball check valves** are similar to lift checks, except that they use a ball rather than a disk to accomplish closure. Some ball checks are specifically designed for horizontal flow or vertical upflow installation.

**Wafer check valves** are designed to fit between pipe flanges similar to butterfly valves and are used in larger piping (4 in. diameter and larger). Wafer check valves have two basic designs: (1) dual spring-loaded flapper, which operates on a hinged center post, and (2) single flapper, which is similar to the swing check valve.

In **silent or spring-loaded check valves**, a spring positively and rapidly closes a guided, floating disk. This valve greatly reduces water hammer, which may occur with slow-closing check valves like the swing check. Silent check valves are recommended for use in pump discharge lines.

### STOP-CHECK VALVES

Stop-check valves can operate as both a check valve and a stop valve. The valve stem does not connect to the guided seat plug, allowing the plug to operate as a conventional lift check valve when the stem is in the raised position. Screwing the stem down can limit the valve opening or close the valve. Stop-check valves are used for shutoff service on multiple steam boiler installations, in accordance with the ASME *Boiler and Pressure Vessel Code*, to prevent backflow of steam or condensate from an operating boiler to a shutdown boiler. They are mandatory in some jurisdictions. Local codes should be consulted.

### BACKFLOW PREVENTION DEVICES

Backflow prevention devices prevent reverse flow of the supply in a water system. A **vacuum breaker** prevents back siphonage in a nonpressure system, while a **backflow preventer** prevents backflow in a pressurized system ([Figure 29](#)).

#### Selection

Vacuum breakers and backflow preventers should be selected on the basis of the local plumbing codes, the water supply impurities involved, and the type of cross-connection.

**Impurities** are classified as (1) contaminants (substances that could create a health hazard if introduced into potable water) and (2) pollutants (substances that could create objectionable conditions but not a health hazard).

**Cross-connections** are classified as nonpressure or pressure connections. In a nonpressure cross-connection, a potable-water pipe connects or extends below the overflow or rim of a receptacle at atmospheric pressure. When this type of connection is not protected by a minimum air gap, it should be protected by an appropriate vacuum breaker or an appropriate backflow preventer.

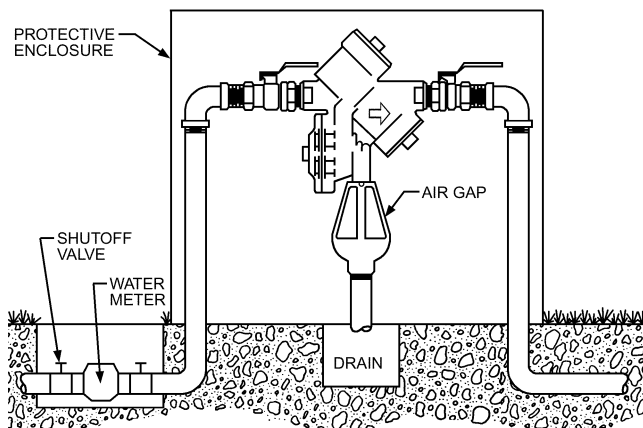


Fig. 29 Backflow Prevention Valve

In a pressure cross-connection, a potable-water pipe is connected to a closed vessel or a piping system that is above atmospheric pressure and contains a nonpotable fluid. This connection should be protected by an appropriate backflow preventer only. Note that a pressure vacuum breaker should not be used alone with a pressure cross-connection.

Vacuum breakers should be corrosion-resistant. Backflow preventers, including accessories, components, and fittings that are 2 in. and smaller, should be made of bronze with threaded connections. Those larger than 2 in. should be made of bronze, galvanized iron, or fused epoxy-coated iron inside and out, with flanged connections. All backflow prevention devices should meet applicable standards of the American National Standards Institute, the Canadian Standards Association, or the required local authorities.

#### Installation

Vacuum breakers and backflow preventers equipped with atmospheric vents, or with relief openings, should be installed and located to prevent any vent or relief opening from being submerged. They should be installed in the position recommended by the manufacturer.

Backflow preventers may be double check valve (DCV) or reduced pressure zone (RPZ) types. Refer to manufacturers' information for specific application recommendations and code compliance.

### STEAM TRAPS

For a description and diagram of these traps, refer to [Chapter 10](#).

### REFERENCES

- ASME. 1996. Valves—Flanged, threaded, and welding end. *ANSI/ASME Standard B16.34-1988*. American Society of Mechanical Engineers, New York.
- ASME. 1998. *Boiler and pressure vessel code*. American Society of Mechanical Engineers, New York.
- ASME. 1998. Rules for construction of power boilers. *Boiler and pressure vessel code*, Section I-98. American Society of Mechanical Engineers, New York.
- ASME. 1998. Rules for construction of heating boilers. *Boiler and pressure vessel code*, Section IV-98. American Society of Mechanical Engineers, New York.
- ASME. 1998. Rules for construction of pressure vessels. *Boiler and pressure vessel code*, Section VIII-98. American Society of Mechanical Engineers, New York.
- Fairbanks Morse Pump Company. 1965. *Hydraulic handbook*. Catalog C and #65-26313. Beloit, WI.
- FCI. 1991. Control valve seat leakage. *ANSI/FCI Standard 70-2-91*. Fluid Controls Institute, Cleveland.
- ISA. 1995. Flow equations for sizing control valves. *ANSI/ISA Standard S75.01-85 (R 1995)*. International Society for Measurement and Control, Research Triangle Park, NC.
- ISA. 1996. Control valve capacity test procedures. *ANSI/ISA Standard S75.02-96*. International Society for Measurement and Control, Research Triangle Park, NC.
- Jordan, C.H. 1998. Terminology of pressure relief devices. *Heating/Piping/Air Conditioning* 70(9):47-48.
- Lyons, J.L. 1982. *Lyons' valve designer's handbook*, pp. 92-93, 209-210. Van Nostrand Reinhold, New York.
- Ulaniski, W. 1991. *Valve and actuator technology*. McGraw-Hill, New York.

### BIBLIOGRAPHY

- ASHRAE. 1988. Practices for measurement, testing, adjusting and balancing of building heating, ventilation, air-conditioning and refrigeration systems. *ANSI/ASHRAE Standard 111-1988*.
- ASHRAE. 1996. The HVAC commissioning process. *Guideline 1-1996*.
- ASME. 1994. Pressure relief devices. *ANSI/ASME Performance Test Code PTC 25-94*. With Special Addenda (1998). American Society of Mechanical Engineers, New York.
- Baumann, H.D. 1998. *Control valve primer*, 3rd ed. International Society of Measurement and Control (ISA), Research Triangle Park, NC.

- Borden, G., Jr. and P.G. Friedmann, eds. *Control valves*. International Society of Measurement and Control (ISA), Research Triangle Park, NC.
- CIBSE. 1985. Automatic controls and their implications for system design. *Applications Manual AM1*. The Chartered Institution of Building Services Engineers, London.
- CIBSE. 1986. *Guide B: Installation and equipment data*. The Chartered Institution of Building Services Engineers, London.
- Crane. Flow of fluids through valves, fittings and pipe. *Technical Paper 410*. Crane Valve Group, Long Beach, CA.
- Gupton, G. 1987. *HVAC controls: Operation and maintenance*. Van Nostrand Reinhold, New York.
- Haines, R.W. 1987. *Control systems for HVAC*. Van Nostrand Reinhold, New York.
- IEC. 1987. Control valve terminology and general considerations. Industrial-process control valves, Part I. IEC *Publication 60534-1*. International Electrotechnical Commission, Geneva, Switzerland.
- Matley, J. and Chemical Engineering. 1989. *Valves for process control and safety*. McGraw-Hill, New York.
- McQuiston, F.C. and J.D. Parker. 1993. *Heating, ventilating, and air conditioning: Analysis and design*, 4th ed. John Wiley & Sons, New York.
- Merrick, R.C. 1991. *Valve selection and specification guide*. Van Nostrand Reinhold, New York.
- Miller, R.W. 1983. *Flow measurement engineering handbook*. McGraw-Hill, New York.
- Zappe, R.W. 1998. *Valve selection handbook*, 3rd ed. Gulf Publishing, Houston.

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