# Control Valve Selection For Hydronic Systems

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Water is one of the primary distribution media for heating or cooling energy in large buildings. This energy is imparted through heat exchangers (coils), normally part of an air-handling unit. The traditional method of control is to throttle the flow of water, air or both in proportion to space or air-handler discharge air temperature. When water flow is throttled, a control valve performs the function. This article discusses some of the effects of the valve in operation and ideas for proper valve selection. Understanding control valve performance is required to operate the system efficiently, tune temperature controllers, minimize interaction effects on other parts of the HVAC system, reduce operating cost and keep people comfortable.

For the purposes of this discussion, we'll define a simple system. *Figure 1* shows a blower, coil, valve, controller, and a source of water for heating or cooling. We will assume constant air volume. We will define a constant water temperature to the coil and constant entering and leaving pressures. This simplification allows us to define a supply air temperature that will maintain comfort. If it's too cold, add more heat; too hot, take some heat away by changing the flow of water to the coil.

Traditionally, the temperature controller has been a simple device relying on proportional control logic. Even sophisticated direct digital controllers rely on the same fundamental logic. With proportional logic, as the error (difference between the controller setpoint and the measured variable [air temperature]) increases, the controller output changes the flow of water and resulting heat transfer to reduce the error (temperature difference).

Proportional control is a linear function. It assumes that 20% output will produce 20% heat transfer. On the other hand, the coil heat exchange process tends to be non-linear. *Figure 2A* is a typical heating coil characteristic, and *2B* is for cooling. These coil characteristics, which are borrowed from the *ASHRAE Handbook — Applications,* show that 20% flow to the coil yields far greater that 20% sensible heat transfer. It yields about 60% sensible heat transfer.

Coil characteristic varies with airflow, entering water temperature, differential temperatures, water velocity and construction. For example, lowering the waterside temperature difference tends to make the early response very steep. At 6°F (3°C) water temperature differential, 10% flow produces on the order of 70% sensible heat transfer. A higher ΔT, such as 16°F (9°C), might give a response similar to 35% sensible transfer at 10% flow. Each coil needs to be evaluated for its individual characteristic.

Control valves link the logic of the controller to the coil. Three valve characteristics typical in HVAC are quick opening, linear and equal percentage. The equal percentage valve is used for temperature control due to the complementary nature of the valve characteristic with the coil. *Figure 3* illustrates the "marriage" of the coil and valve to present a "linear" heat transfer function.[1] At 50% stroke (equivalent to the controller at 50% output), there is about 15% flow, which is about 50% sensible heat transfer. This integration of components to achieve a linear process allows the controller to work with a single gain (proportional band). If the response of the valve and coil were different, multiple gains would be required.

Sizing the valve primarily requires selecting the valve flow coefficient ($C_V/K_V$). Valve $C_V/K_V$ is developed using water and is the flow of water in gpm (m³/hr) across a wide-open valve at a pressure drop of 1 psi (1 Bar). The flow through the valve (Q) equals the $C_V$ times the square root of the differential pressure across the valve ($Q = C_V \times \sqrt{\Delta P}$). Fluids other than water require an adjustment for their specific gravity.

When designing a hydronic system, we know the flow. The flow selection is dominated by design decisions on heat transfer, which can change the shape of the coil characteristic. The pressure difference across the valve is a design decision. This decision is based on evaluating the branch hydraulic losses and the heat transfer characteristic of the coil. Knowing the flow and design pressure difference allows the flow equation to be rear-

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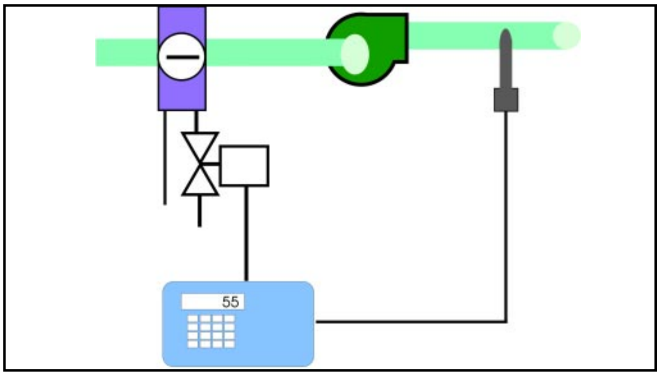

Figure 1: Simple modulating control system.

ranged to solve for $C_V$ ($K_V$). Often, the required $C_V$ ($K_V$) will be between two valve sizes, leaving the designer with a choice of whether to "round up" or "round down." The performance of both valve sizes should be evaluated to determine the best choice.

The combination of the valve and the coil is a theoretical response. Actual conditions such as coil pressure drop affect valve performance and controller response. For proper function, we have to account for operation during the project design stage. Using $C_V$ ($K_V$) allows us to evaluate the branch flow using the flow equation. The rated valve characteristic ($C_V/K_V$) shows flow with the entire branch pressure drop across the valve. There are no other components in the system. Adding fittings, pipe, coils, and other valves imparts other losses in the controlled circuit.

Examining the circuit components as separate parts, it becomes evident that there is a constant $C_V$ ($K_V$) for the coil, pipe and fixed position valves, and a variable $C_V$ ($K_V$) of the control valve (*Figure 6*). The Darcy-Weisbach equation shows that head loss in straight pipe varies as the square function of the flow. A coil is a special case of straight pipe, and although there are return bend fittings, these act in effect as straight pipe.[2] As the valve throttles, its flow coefficient is reduced while the other circuit components remain constant.

The differential pressure delivers a flow in the circuit proportional to the branch flow coefficient. This flow is not as predicted by the valve characteristic curve alone because the other components influence the circuit. Depending on the relative $C_V$ ($K_V$) of the control valve and the other components, the other components might have a greater influence on the flow through the circuit than the control valve.

The concept of valve authority is useful in illustrating this phenomenon and how it affects differential pressure selection of control valves. Valve authority (β) is the ratio of the pressure drop across the valve to the pressure difference across the entire branch, including the valve, as shown in *Figure 4.* Authority will always be less than one. The smaller the authority, the larger the control valve and vice versa.

We can combine the flow coefficient of the valve with a flow coefficient calculated for other components in the circuit that the valve controls by using the following equation:

$$1/(C_V)^2 = 1/(C_{V1})^2 + 1/(C_{V2})^2 + 1/(C_{V3})^2 + \ldots$$

If there are only two components in the circuit, this equation

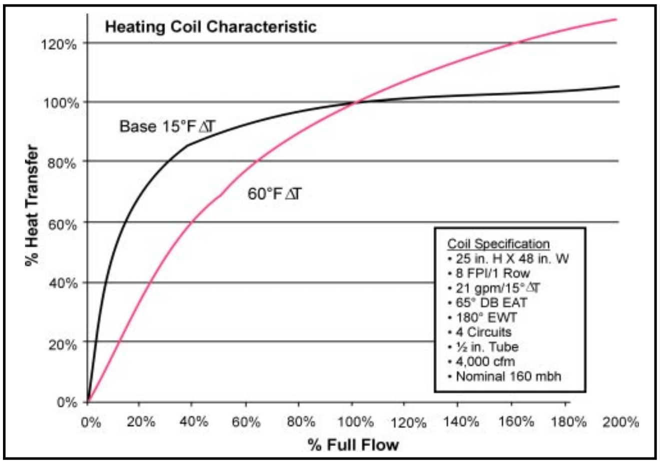


Figure 2a: Typical heating coil characteristic. This characteristic curve is similar to that shown in the *ASHRAE Handbook—Applications,* Chapter 36, Page 8, Figure 3. It was developed using a manufacturer's coil-sizing program and a spreadsheet for plotting.

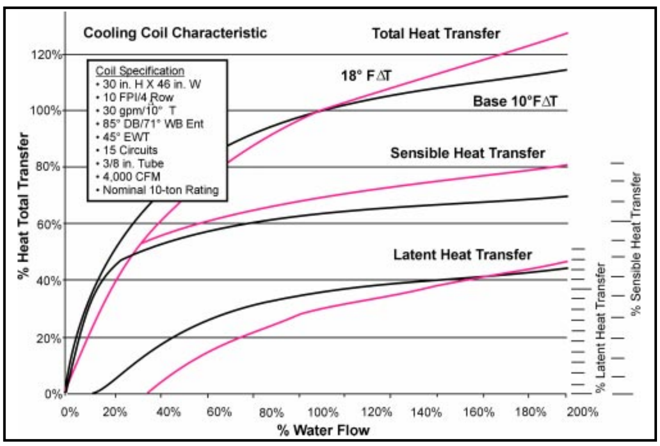


Figure 2b: Typical cooling coil characteristic. This characteristic curve is similar to that show in the *ASHRAE Handbook—Applications,* Chapter 36, Page 8, Figure 4. It was developed using a manufacturer's coil-sizing program and a spreadsheet for plotting. Although similar for the characteristic shape of "total heat," it is different for "latent heat."

reduces to:

$$C_V = (C_{V1} \times C_{V2})/\sqrt{[(C_{V1})^2 + (C_{V2})^2]}$$

*Figure 5* is a plot developed by calculating an equivalent $C_V$ ($K_V$) for the circuit. It shows flow in the branch against the stem height of the valve at various valve authorities. An authority of 0.5 represents a valve with one-half of the circuit pressure drop, while 0.1 represents one tenth.

These "branch" control characteristic curves can then be compared to the coil heat transfer characteristic in *Figure 2A* or *B*. Where previously (before considering authority) the controller wanting 50% heat transfer got a stem position of 50% and flow percentage of 15%, at an authority of 0.5, 50% stem travel allows 22% of the design flow and delivers 60% to 65% of heat transfer. This performance is not exactly linear, but it is not bad. With an authority of 0.1, 50% stem travel yields a flow of 58% and more than 90% heat transfer. The lower the valve authority, the less linear the control output (stem position) versus heat transfer characteristic, making tuning the controller difficult with the total operating range of the valve.

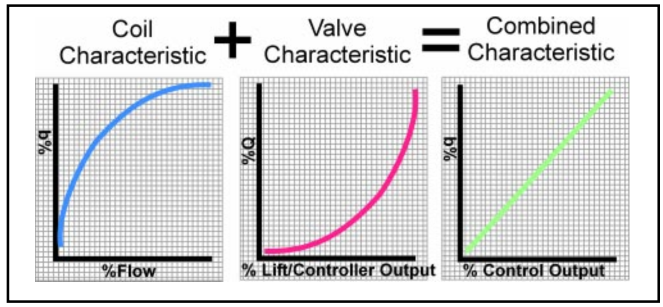


Figure 3a: Typical coil and valve characteristic "marriage." The combined coil heat transfer characteristic, with valve characteristic shown for 50% authority for a cooling coil. Note the "hump" due to the rapid increase heat transfer with early flow.

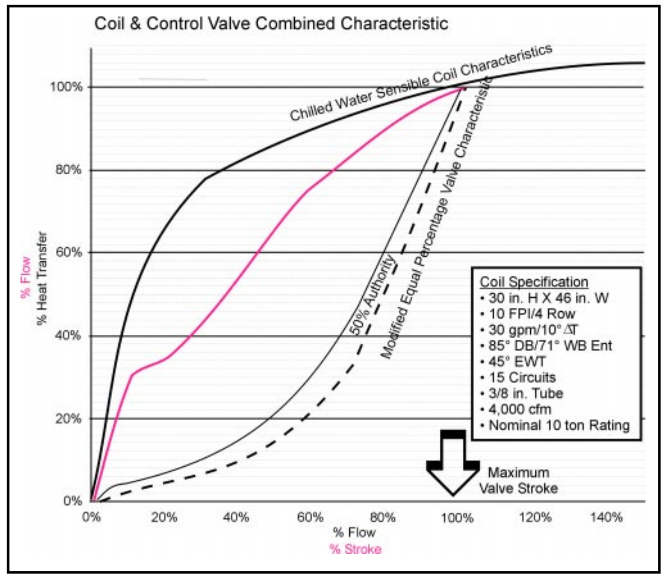


Figure 3b: Typical control characteristic with control valve. The combined coil heat transfer characteristic, with valve characteristic shown for 50% authority for a cooing coil. Note the "hump" due to the rapid increase heat transfer with early flow.

Selecting the design differential pressure for the control valve becomes critical if controlling the circuit flow and heat transfer is important. Poor valve selection implies poor flow performance across the operational range of the valve. To compensate for this problem, the controller will be tuned at its most common operating conditions, which will likely be at a minimal stroke range of the valve.

Depending on location, the facility's cooling load could be less than 50% most of the time. If the controller must be tuned to respond to 0% to 20% of stroke because of an over-sized valve, overflow conditions can easily develop in the circuit. This overflow can create a condition of hydronic imbalance,

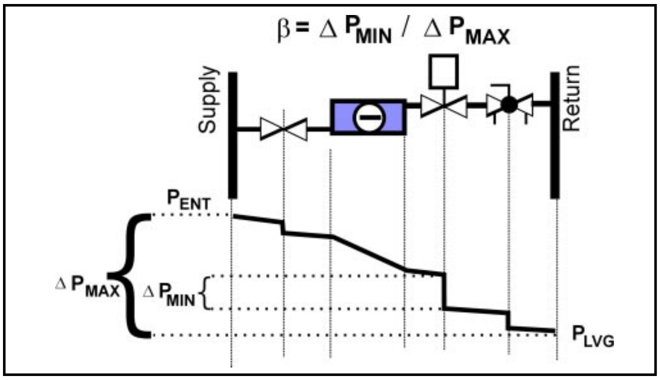


Figure 4: Defining valve authority on a circuit level.

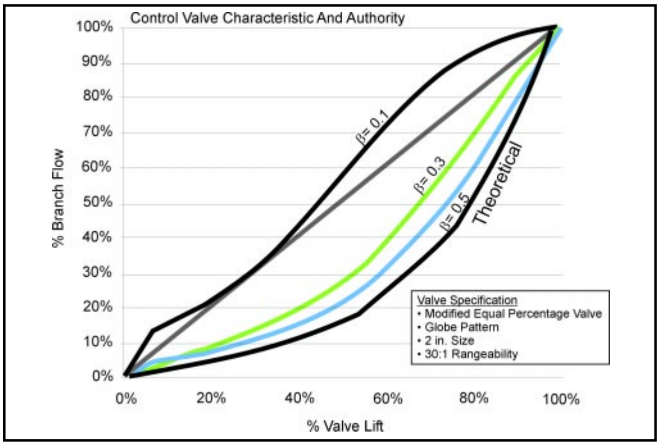


Figure 5: Typical equal percentage valve characteristic with authority. Valve characteristic shown for 50%, 30% and 10% authority. Valve base characteristic is modified equal percentage to provide "zero" flow at "closed" valve stroke.

where other circuits of the system receive less than required water flow. These other controllers will seek to open their respective valves, flowing more water, resulting in more pump energy and poorer plant performance.

Engineers should not assume that temperature controllers would be sensitive enough to see the overflow and react to it. The coil heat transfer characteristic (*Figure 2*) shows that a 100% overflow (200% of design flow) produces a small increase in sensible heat transfer for heating and cooling. As an example, a low differential temperature (6°F/3°C Δ*T*) chilled water design will have about 5% more sensible heat transfer. High differential temperature designs (16°F/9°C Δ*T*) will have around 15% more sensible heat transfer. These factors will vary with coil construction.

Flow control is but one issue that can arise from this situation. Other issues that might be seen because of poor selection are:

• **Worse low-end performance:** being mechanical devices, valves have inherent limitations due to design. Valves lose their ability to control flow accurately at stem positions near close off. This effect is quantified as valve rangeability, the ratio of maximum-to-minimum controllable flow. Typically, globe valves selected for HVAC application have rangeability of 30:1 when sized 2 in. (51 mm) or less, and less than 10:1 when more than 2 in. (51 mm) in size. This means that small valves have a minimum pre-

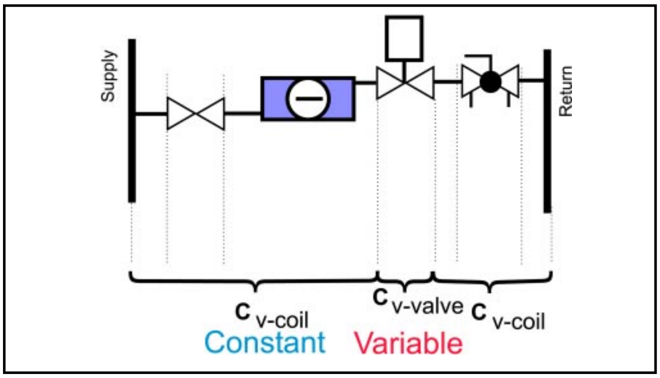


Figure 6: Valve relationship with branch. Being motorized and adjustable by the temperature controller, the valve CV constantly changes to adjust flow to the branch. The Darcy-Weisbach equation shows in the static elements of the branch that pressure loss will change as a function of the square as long as the dimensions of the fittings has not changed.

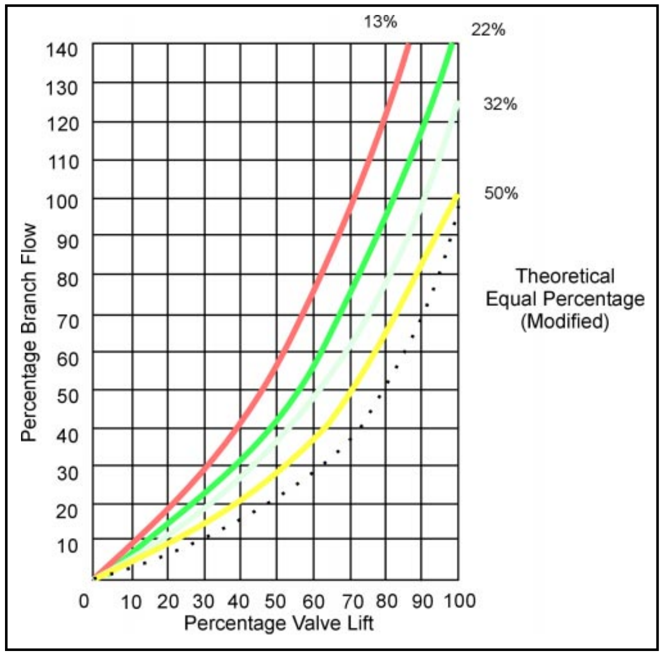


Figure 7: Valve authority with respect to system with branch equal to 50% (Petitjean).

dictable and controllable flow of 3.3%, which is about 0% to 10% of stroke. Valve authority distorts the theoretical characteristic curve that valve manufacturers use to report rangeability. In his work *Total Hydronic Balancing: A Handbook For Design and Troubleshooting of Hydronic HVAC Systems*, Robert Petitjean reports that the actual minimum flow is the rated minimum controllable flow divided by the square root of the authority ($Q_{ACT} = Q_{MIN}/\sqrt{\beta}$). This distortion raises the minimum controllable heat transfer from a moderate value of 6% to 20% or more, depending on control valve authority.

• **Potential for damage to the valve and actuator:** because of poor flow control at the low end, tuning becomes more difficult and the controller tends to react in an "on/off" manner. When a controller reacts proportionally, it "sits" at one position delivering a required flow. If the minimum controllable flow is too high, the controller will probably hunt, developing an oscillation of opening and closing. This might not be obvious from a temperature perspective in the HVAC system, but it can cause unnecessary wear on components of the valve such as packings, seats, actuators, etc.

• **Valve Cavitation:** operating at reduced opening might cause damage from valve cavitation. Cavitation can occur when the pressure drop across the control valve opening is too high. The combination of pressure drop through the plug and velocity increase at the vena contracta cause the pressure on the surface of the water to fall below its vapor pressure and form steam bubbles. As the pressure recovers downstream, the steam bubbles implode with tremendous force. The limited area where occurs can cause significant damage to the valve seat and plug. The risk of cavitation tends to occur most in hot-water systems when taking pressure drops greater than 15 psi (103 kPa) across the control valve. It depends on the valve construction and materials, and the point of occurrence will vary by manufacturer. Although cavitation is not common, it is worth checking with the valve supplier during the design stage.

• **High Maximum Δ*P*:** Cavitation also may be noticed in a slightly more understated but overlooked manufacturer specification of maximum differential pressure. Most HVAC control valves are rated for differential pressures no greater than 35 psi (81 ft/240 kPa). This can be quite limiting. Many larger hydronic systems are sized with pump heads 100 ft (43 psi/300 kPa) or greater. Even in smaller systems, 100 ft/300 kPa pump head seems to be a common selection. If the hydronic system design allows valves to close completely against the full pump head without any further system adjustments, damage to the valve can occur. In particular, globe valves "leak," so even if they are technically closed, industry standards allow for some minimal leakage. In the extreme, a process of wire drawing or erosion can occur, mechanically damaging the valve. In a simple system, the actuator might stop functioning properly, either forcing flow in a pneumatic system or stalling an electronic actuator.

• **Valve De-rating:** we've purposely limited the discussion to two-way globe valves. When tested to industry standards, valves are rated with line-size piping. When combined with reducers (smaller valve than pipe), there may be a reduction in effective valve flow coefficient. While this generally is not a concern with the globe valve, the effect can be considerable for valve styles such as ball and butterfly that have much larger flow coefficients for similarly sized valves. While on the surface this may seem a positive, the larger $C_V$ means that the valve size will be much smaller than the corresponding piping. Selecting the proper $C_V$ for these types of valves requires correcting for piping geometry. Depending on the size of the pipe and valve, the associated reduction in flow coefficient may be substantial. Driskell's *Control Valve Sizing* offers tutelage on the subject, but he notes that there is minimal corroborated test data on fitting correction factors. Several valve suppliers publish their flow coefficients for line-size piping with various combinations of reducers. This is helpful because often this data is derived by test and not calculation, leading to a better selection.

Valve authority and valve-differential pressure are limited in scope and only consider the flow of the circuit. The entire hydronic system should also be analyzed for flow and operation. Exercise care in the following areas:

• The same analysis of authority can be done for the valve effect on its total hydronic circuit. The effects of the supply and return risers, as well as any other associated equipment being pumped on the same circuit means varying differential pressure. As the system control valves close, there is less loss in the piping and coils. As a result, the effective valve authority becomes the ratio of the pressure drop of the valve fully open to the pump head (Petitjean). A series of curves similar to *Figure 7* can be developed to show the effect of the valve $\Delta P$ against the system $\Delta P$ (the pump head). An authority of 0.25 or greater (the valve taking 25% of the pump head as a drop when fully open) is suggested for stable control.

• In a constant speed pumping system, stroking a branch-control valve will change system flow. Flow in all other circuits also will change as a function of their location. Typically, constant speed/constant flow systems are not designed with two-way control valves for fear of damage to equipment at low or no flow. If the design uses constant speed-pumping and constant system-flow, three-way valves are often used. The mistaken impression of the three-way valve is that it is a "constant flow" valve. Properly selected and applied with a balancing valve in the bypass leg to make bypass loss equal to coil loss, it is assumed that total flow across the valve remains constant regardless of stem position.

Three-way valve systems are rarely constant flow. Generally, rated valve flow only exists at full terminal flow or full bypass flow. As a result, the system either overflows or underflows depending on the valve plug characteristic, authority and stem position. With a linear characteristic valve at 50% stem position and 50% authority, the system would have about 135% flow. Depending on how many valves and how the pump motor was sized, this flow might overload the motor if it was not sized for non-overloading operation. Underflowing will occur with an equal percentage valve selected at 50% authority. Reducing flow rides up the pump curve and does not risk overloading the motor. However, depending on the slope of the pump curve, you could very well reach the control valve's maximum differential pressure. Often, it is better to consider a variable speed/variable flow hydronic system to capture the energy savings.

## Conclusion

Control valve differential pressure selection is considered by many to be part art, part experience. Over time, several rules of thumb have been established for sizing control valves. These rules may work well sometimes and perform poorly at others. If we attempt to draw a generalized conclusion on differential pressure selection for valve sizing, selecting differential pressure for a control valve branch authority of 50% has been used with reasonable results. However, $\Delta P$ should really be optimized to the coil selection based upon its design characteristic as a start. Large coil differential water temperatures selections can provide "flatter" coil characteristics. Then, an authority less than 50% might achieve linear heat transfer and be appropriate. The lower authority implies less pressure drop across the valve and possibly less pumping energy.

Much needs to be understood and manipulated for the proper selection of control valves. Aside from the valve itself, consideration must be given to the system as a whole. Valve authority has been referred to in many different ways for more than fifty years. Rules of thumb like "valve size one size smaller than pipe," or "pressure drop equal to coil drop" or "5 psi (34 kPa)" all hail from the pressure relationships that authority helps illustrate.

## Notes

1. Manufacturers have a variety of modifications to the equal percentage characteristic. Generally there is a 45% change in flow for every 10% of stroke. Near close off, this varies because of the math. If you start from zero flow, a 45% increase in flow is still zero. The result is that at the low-end, the characteristic is not truly an equal percentage.

2. Much research is being done on fitting losses. While some engineers use the "K" factor method to predict loss, others use total equivalent length (TEL) or a simple multiplier. Current research is refining these predictive measures. The result is that losses in a bulk component such as a coil probably do not have head losses to the square power of the traditional Darcy equation. The exponent may be less than two, due in part to the number of fittings versus the quantity of straight pipe and fitting loss values that have been overstated for many years.

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