PICVs and VRFs: *Two Sides of the Same Coin*

A look at how pressure independent control valves are increasingly being accepted as synonomous with variable-flow control.

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Images courtesy of Danfoss.

Variable-flow systems

Today, rising energy prices and a focus on energy-efficient, green building technology and design are affecting the viability of constant-flow hydronic systems in HVAC system design. Not only are constant-flow hydronic systems costly to operate, but they do not make good use of energy-saving technologies like variable-frequency drives, speed-controlled pumps and variable-flow chillers.

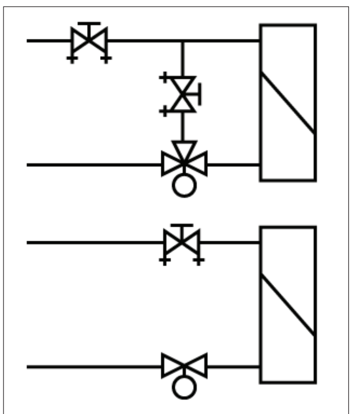

Figure 1 A Constant-flow system (top) and a variable-flow system (bottom).

There is a reason ASHRAE Standard 90.1 requires variable flow for most systems and VFDs for 5 hp and more. In fact, two-way valves as a part of variable-flow systems have been around for decades. However, valve technology for these installations has not advanced at the same rate as other modern components. Most designs today still use the two-way valves and balancing valves that are almost the same valves used 80 years ago, except for an improvement in the control ratio. Even those valves were adaptations of existing technology used for three-way (constant-flow) systems.

A legitimate question to ask would be if innovation is really needed. "If something is not broken, don't fix it" is a platitude that most engineers could get behind. It is, however, easy to point out the challenges caused by the use of two-way and balancing valves.

Low ΔT

One of the most important parameters when it comes to operating an energy-efficient installation is the ΔT in the system. Low ΔT will cause problems with chillers and reduce the efficiency of the whole installation, wasting energy. We do not think we are revealing a big secret when we say that most installations do not run on their designed ΔT immediately after commissioning. So how is this possible?

One of the reasons can be seen in Figure 2. It depicts a typical water-air heat exchanger as it can be found in fan-coil units and air-handling units and, in this particular case, a cooling coil. What we see is that as soon as the flow exceeds 100%, it no longer contributes to cooling the building. Doubling the flow will increase the coil capacity by only 10%. The increased speed through the coil gives the water less time to transfer the heat energy to the air and, therefore,

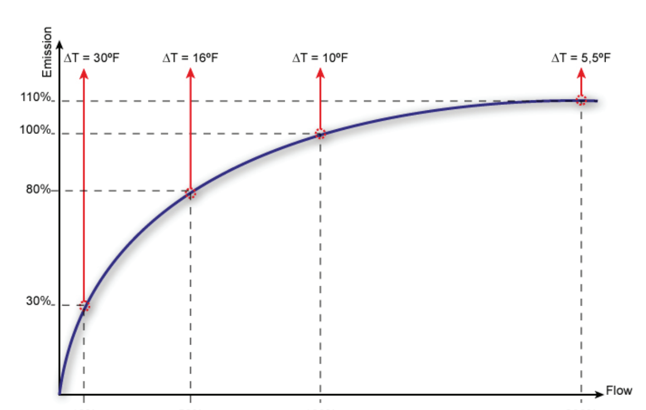

Figure 2 Coil characteristic.

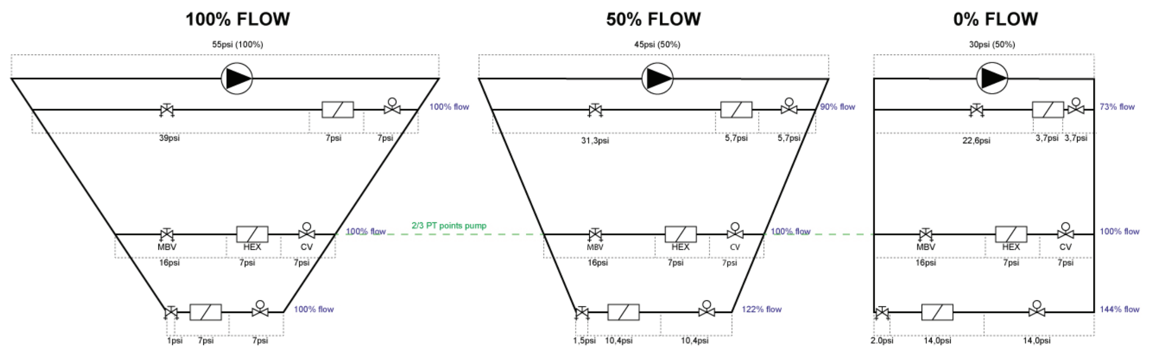

Figure 3 Pressure distribution for different flows in the system.

the ΔT over the coil is drastically reduced. So, if an open control valve will allow more flow than was designed, i.e. in case of missing balancing valves, you will get a reduced ΔT and almost no increase in actual energy transmission into the room.

There is a belief that balancing is not needed, as control valves (ATC) are always controlling the flow below the nominal flow. The PI control has a very limited influence on balancing. For starters, as soon as the temperature goes outside of the P-band, as in start-up mode or when there is a sudden high load demand on a room, the valve will be fully opened, as can be seen in Figure 2. If the available pressure for that valve is higher than designed (system load <100%), overflow will occur and that overflow will cause a low ΔT condition. Many engineers consider this to be transient issues, only temporarily upsetting the equilibrium in the system. However, because of better insulation and building construction, outside influences have only a minor influence on the load in the building and it is more the people and the equipment that influence it. Therefore, people moving around in the building and switching equipment on/off are constantly causing fast disturbances in the load. The issue goes from being transient to a permanent state of affairs.

Even if the control is operating within the P-band, we are still not out of the woods. For lower loads we need low flows. For 80% coil capacity we only need 50% of the flow through the coil, and for 30% we need only 10% of the flow. It is difficult to control these flows using normal control valves if you have authority or turn-down issues. When these low-flow-required conditions arise, the control will start to behave on/off so you have either no flow or too much. Too much flow will always mean a sub-optimal ΔT, so balancing and control issues are the root cause of many problems.

Differential pressure issues

Water wants to follow the path of least resistance. This causes imbalances in the system where terminal units closest to the pump get too much water, while terminal units at the end of the system get too little. This issue is usually solved with manual balancing valves. The balancing valves are used to increase the resistance in the circuit so the water is redirected to other parts of the system.

Even though a balancing valve is a very simple device, making sure it is set properly is another matter altogether. Even if it is done properly, what did we achieve? Balance for the 100% system load in the installation, which is least likely to occur. So, we could ask if it is even worth installing them.

When the installation is only partially loaded, which is more than 95% of the time, we run into the limitation of the balancing valve and its inability to react to changes in the operating conditions. Because valves will start to close, the dynamics in the system change and the available differential pressures (ADP) will rise. Rising differential pressures mean higher flows. Speed-controlled pumps may provide partial relief for this problem, but it is not the panacea it is usually made out to be, as can be seen in Figure 3.

The figures represent the pressure drops in a sizeable system where all the terminal units are the same and need the same flow. The leftmost figure represents the pressure drops at full flow (the control valves are sized to the suspect size-to-terminal-unit-pressure-drop method). The balancing valve closest to the pump takes considerably more pressure than the one at the end of the installation. The green line represents two-thirds of the installation.

Now observe what happens to the pressure when we reduce the flow to 50%, as can be seen in the middle figure. The circuit at two-thirds of the installation pressure is still fine, since the pressure is kept constant at the measuring point. However, the ADP for the other circuits is changing. The circuit closest to the pump now has an underflow, even with the valve fully open. If the valve in the circuit furthest from the pump is fully open, as is likely to happen when the control is outside of its P-band, it has an overflow. When the system is on very low loads, or close to 0% flow, as can be seen on the right side of Figure 3, the problem intensifies with bigger over- and underflows occurring.

If the installation is complicated with a lot of branches, it is sometimes difficult to determine where the proper place on the installation you should install the Pressure Transmitter (PT) points of the pump. Based on Figure 3, you can now make a

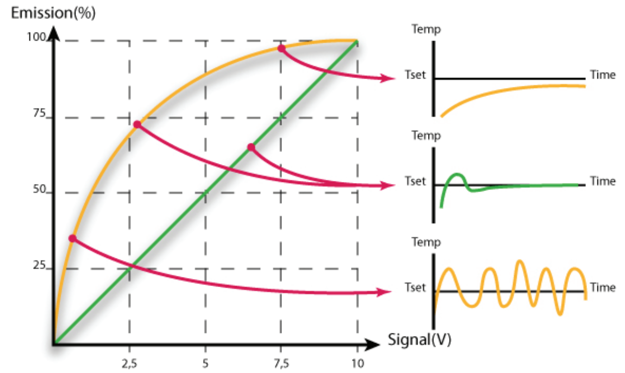

Figure 4 Only linear responses will lead to stable control. Too steep will mean instability, and too flat will mean a too-slow reaction at increasing signal.

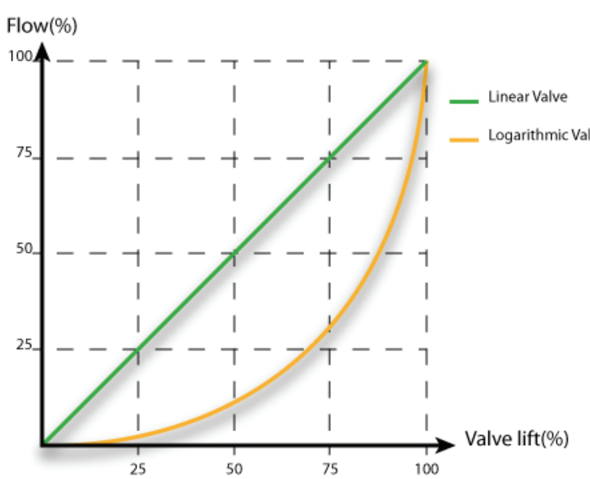

Figure 5 Control valve characteristics.

judgment on which side you would like to err. Putting them too close to the pump will increase overflows and will, therefore, reduce the energy efficiency; putting them at the end of the installation (as suggested by Standard 90.1) will increase the underflows and, therefore, increase complaints. This in turn will lead to higher settings on the pump, decreasing energy efficiency. Either position presents a lose-lose situation, so pick your poison.

Control performance

The precision of the temperature control has far-reaching consequences for the well-being of the buildings' occupants; the amount of energy the building uses; and the maintenance costs it needs. Unfortunately, realizing accurate room-temperature control is not as easy as mounting an actuator on the two-way valves and connecting it to a building-management system. The PI-control can easily maintain stable, precise temperature control if the system response is linear (see Figure 4). Extensive tuning of the control parameters can stabilize the control if the system response is not linear, but only in a certain set of conditions. It would be possible to stabilize the lower quarter of the orange graph in Figure 4 by increasing the P-band and I-time to compensate for the aggressive responses of the system but it would then be way too slow in all other situations.

Authority

If the system reaction must be linear, we need to adjust the valve to the coil. In the case of water-water heat exchangers, the coil behavior will be close to linear so a linear response of a valve can be used. If the coil is water-air, like most of the coils in HVAC systems, the behavior is not linear (see Figure 2). In this case, we need to use a logarithmic response of a valve, sometimes called an equal-percentage valve. As can be seen in Figure 5, the logarithmic valve has a characteristic that is counter to the coil characteristic, which should lead to a linear response from the system.

To select a characteristic that will complement the coil

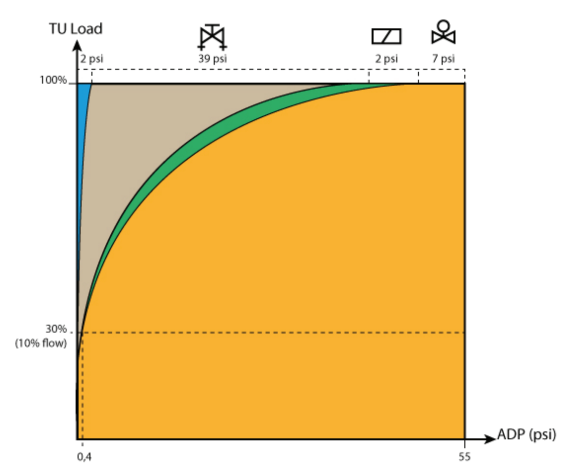

Figure 6 Changing ADP for the control valve.

characteristic is fine in theory, but it should be noted that the valve characteristic is determined at a constant ADP. If we observe what happens to the ADP of the valve closest to the pump, we can see that the pressure rises substantially (see the orange area in Figure 6). This occurs because when the flow is reduced, pressure drops in the rest of the installation are drastically reduced.

One can understand that this rising differential pressure has an effect on the characteristic of the valve. The flow at smaller valve openings will be higher than expected because the ADP is higher than expected. In Figure 7, you can see what the characteristics of the valves could look like as a result of these rising ADPs.

The deformation of the valve characteristic is embodied in the authority of the valve. The authority defines to what degree the control valve can impose its characteristic on the circuit. In other words: how close does the installed characteristic of the valve resemble the theoretical characteristic in the datasheet. It is relatively easy to calculate the valve authority using the following formula:

$$\beta = \frac{\text{ADP open valve}}{\text{ADP closed valve}}$$

Generally, we assume that the authority should at least be 0.5 to guarantee proper control. Even though the authority can be calculated with a simple formula, doing it in an actual installation is not so simple. To start with, the authority of all valves in the installation will be different and is dependent on the placement of the PT points for the pump.

ADP

By calculating the authority you can predict what will happen with a single valve in the installation. It does not take into account the actions of the other valves in the installation. However, in the installation, the valve does not operate alone, as it is part of a system in which many valves simultaneously try to control temperatures. As soon as a valve opens or closes in the system, it changes the ADP for all the other valves installed and, for added complexity, there is a speed-controlled pump that is changing the ADPs for the installation as a whole. The control valve characteristic would therefore in practice look more like Figure 8. It must be understood that this is a snapshot. Because of the dynamics in the system, the ADP will never stay constant. So even if the valve does not move, the ADP, and therefore the flow, will change. In other situations the characteristic could look entirely different.

It is clear that with such a characteristic, a stable control is a pipe dream, even if you would be prepared to change the P- and I-constants on a regular basis.

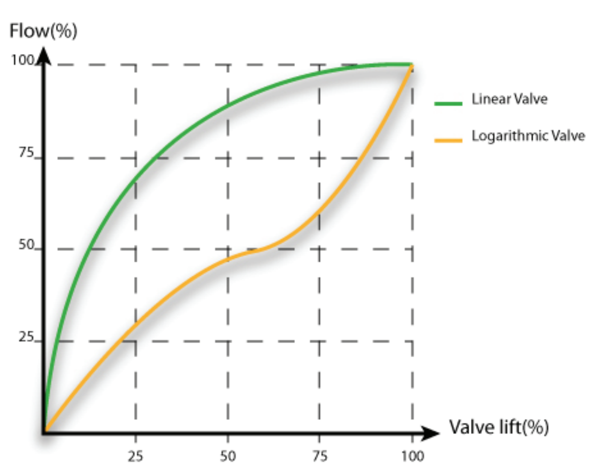

Figure 7 Valve characteristics at low authorities.

Turn-down

Designers are often prepared to spend more money on a valve that has a higher turn-down ratio because they think it will improve temperature control. The turn-down says something about the minimum controllable flow of the valve. A turn-down of 1:50 means that it can reliably control down to 2% of the maximum flow. It is a value that is only relevant for logarithmic valves because they need specially shaped cones that give unpredictable results at small openings. For linear valves, the turn-down is officially equal to the leakage rate.

If there is a low authority, the ADP will rise substantially as the valve is closing. The smallest flow the valve can reliably control will, therefore, be much bigger than expected. To calculate the installed turn-down, we need to multiply the theoretical control ratio with the authority. In our example from Figure 3, that would mean: 1:50 x √7/55 = 1:18 (control ratio x √nominal differential press / max. diff. pressure with closed valve), so real minimum controllable flow rate is close to 5%.

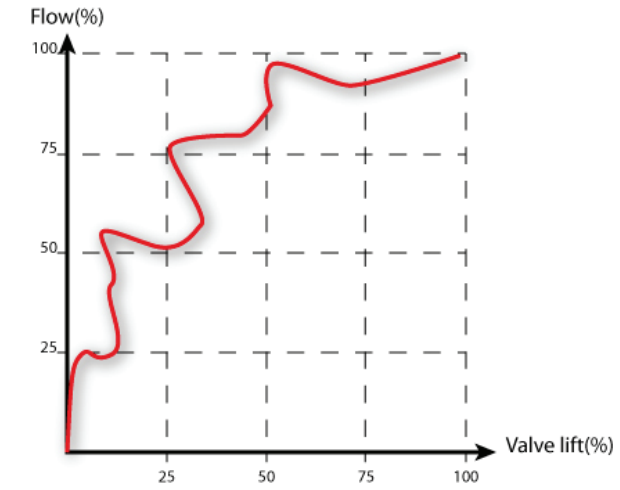

Figure 8 Valve behavior in "real life."

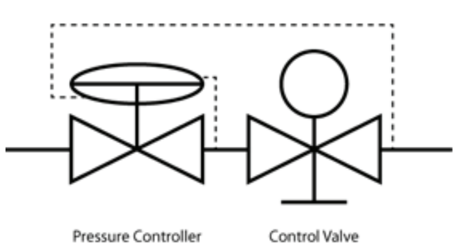

Figure 9 Schematic depiction of a PICV.

PICV

All of the above examples lead to the conclusion that if we can control the fluctuating, unpredictable pressures, we need not worry about balancing, authority or turn-down issues anymore. It so happens there is a valve that does exactly that, it is the pressure independent control valve, which is is not subject to the normal pressure fluctuations in the system.

The valve consists of two parts, a pressure controller and a control valve. The pressure controller keeps a constant differential pressure across the control valve. By keeping the available differential pressure across the control valve constant, it automatically limits the flow because flow = Cv x √ADP, and both the Cv and the ADP are now constant values, which means the flow is also constant. By opening and closing the control valve, you change the Cv and you can, therefore, change the flow in a controlled, predictable way.

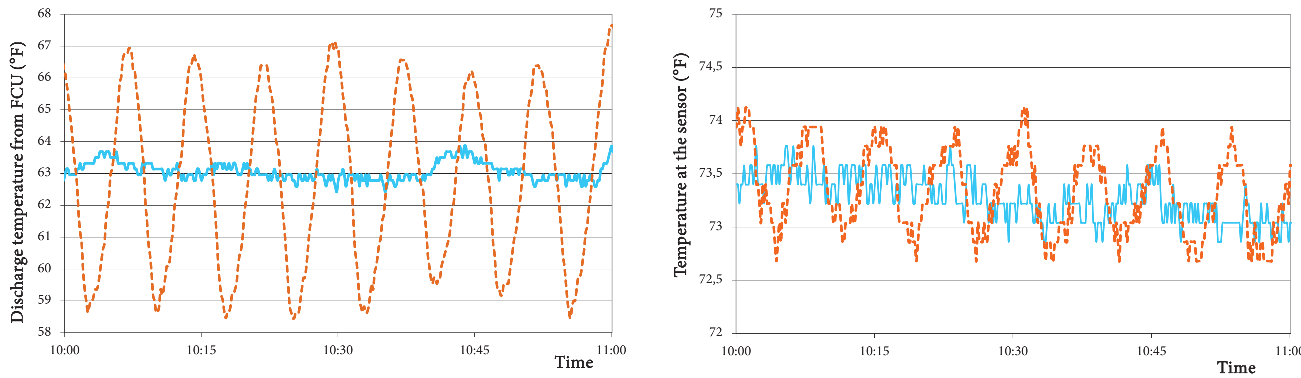

Figure 10 Results: Graphs above depicts temperature of two rooms measured at the sensor mounted on the entering of the air below the FCU and the temperature of the air leaving FCU on a particular day between 10 a.m. and 11 a.m. The blue line represents PICV while red traditional eq% valve. Even though room temperature seems to be controlled in a narrow band, it is evident that the traditional two-way valve has been in on/off mode, changing its position 12 times in an hour.

Balancing the installation is now easy. Because of how PICVs are constructed, they function as an automatic balancing valve (adapts to any system load) and the flow can simply be set without measuring. This eliminates the complicated, mistake-prone balancing procedure that manual balancing valves require.

The authority is also not relevant anymore because it is always 1. As stated above, the authority can be calculated using the formula:

$$\beta = \frac{\text{ADP open valve}}{\text{ADP closed valve}}$$

Since the differential pressure controller inside the PICV makes sure ADP is the same with the valve open and with the valve closed, the formula will always return 1 as the answer. That means that the theoretical characteristic of the valve is also the installed characteristic and will be fully predictable with all ADPs.

The fully predictable characteristic brings another benefit: we can now use linear control valves that do not have turndown issues for all applications, both water-water and water-air heat exchangers. The PICV allows us to program the logarithmic behavior in either the actuator or the BMS, which will return much better results than trying to achieve the same result with logarithmic valves.

Low ΔT

No overflows and stable controls in the installation also means you have an optimized ΔT. As you can see from Figure 2, proper modulation can increase the ΔT. The lower the load of the system, the bigger the ΔT can be. This creates huge advantages for energy-efficient systems.As a result, high energy-efficiency rated buildings all over the world have used PICVs.

Costs

If you compare the PICV solution vs. manual-balancing valves and control valves, a PICV is a very competitive solution. The initial PICV product investment might be slightly higher, but it will quickly be earned back with savings on commissioning and lower energy consumption. Also, complaints as a result from unstable flow controls can be virtually eliminated, reducing operational costs.

Case in point

In Amsterdam, a case study was done in an office building equipped with traditional control valves and wall-mounted induction units. One of the control valves was replaced with a PICV and temperatures were logged to compare the control behavior. The results (see Figure 10) show that the traditional valve was hunting a lot because the PI-control could not cope. The PICV is capable of maintaining a much more stable temperature.

Conclusion

The PICV is a concept that has been designed, from the ground up, for variable-flow systems and the unique challenges that such systems present. It is possible to solve these challenges by doing extensive calculations, very precise engineering and time-consuming tuning of the control parameters. However, in the complex building process with many parties involved and many decisions made outside of the span of control of the engineer in charge of the conceptual solutions, can we be sure that our precise engineering is actually implemented? Pressure independent valves reduce the complexity of designing the system and can help reduce the risk of unstable controls and low ΔT issues, leading to simplicity and robustness of the design. The PICV has proven itself to be a reliable technology over the last decade, and its increasing acceptance in countries all over the world indicates it is the future of variable-flow control.

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