2. The differential pressure across control valves must not vary too much

Common Problems

Problems, typical indicating that condition number two is not met:
- Continuous oscillation of room temperature.
- Room temperatures not reaching required set point at low loads.
- Maintenance problems with control valves and actuators, due to fatigue from hunting.
- Higher energy costs than expected, due to unfavourable control settings to avoid instability.

Background

Variable flow systems are becoming more and more popular, mainly due to the advantages compared to constant flow systems:

- The pumping costs are reduced
- The return temperature is minimised in heating systems
- The return temperature is maximised in cooling systems

But there is one major disadvantage:

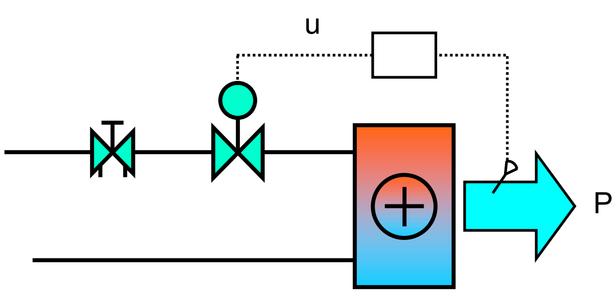
- The differential pressures in the plant may vary considerably during operation

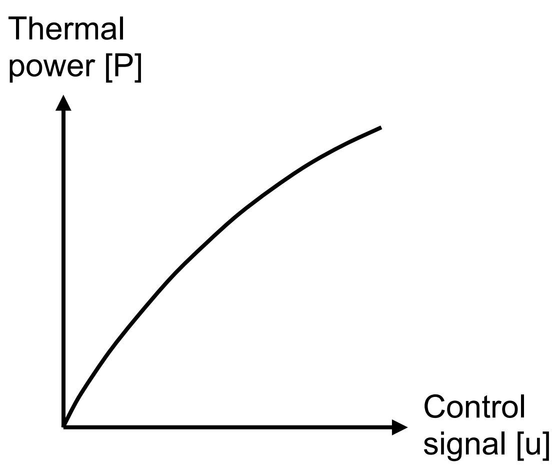
By fulfilling the second condition, the negative impact on system function and performance from this disadvantage can be reduced and even avoided. How it is done? By using good hydronic design!

The essential objective in designing any heating and air conditioning plant is to obtain a comfortable indoor climate, minimising costs and operating problems.
In theory, new control technologies appear adequate to satisfy the most demanding requirements and to provide opportunities for increasing comfort while making substantial energy savings. In practice, however, even the most sophisticated controllers cannot achieve their theoretical performances unless the conditions for their operation are correct. These conditions are settled by the design of the hydronic system. Simply put; control cannot compensate for a poorly designed system, which is why the system must be designed as controllable as possible.

Circuit characteristic

One important measure of hydronic design quality is the circuit characteristic. Fig 1 represents a typical hydronic circuit for an air heating/cooling coil. The circuit characteristic is the relationship between the control signal and the resulting thermal power from the coil. It determines the controllability of the system.



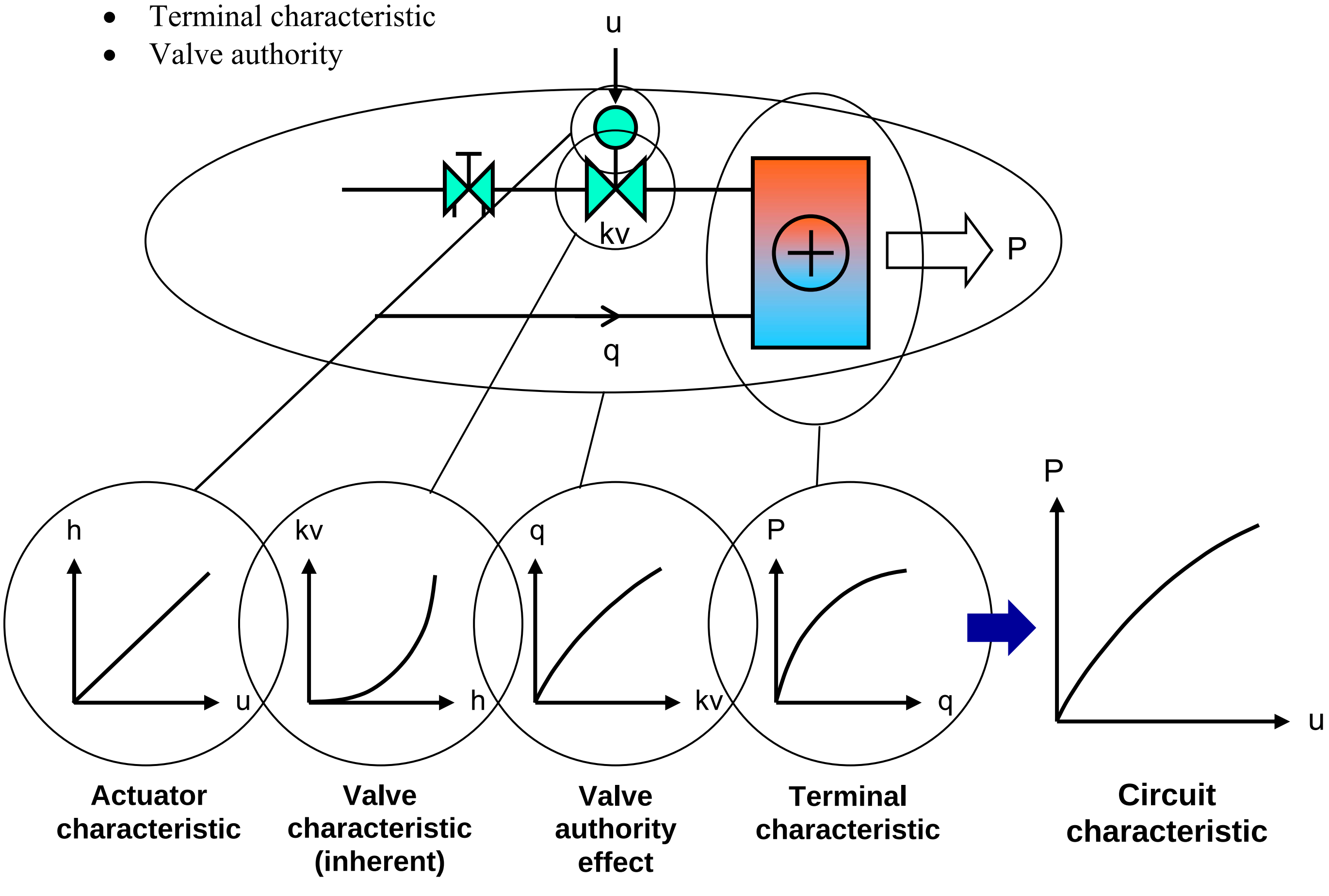


The steeper the slope of the circuit characteristic curve, the higher the risk for control instability becomes and as a result, the more difficult the control becomes. This is quite easy to imagine. At a low slope, any actions from the control will result in marginally changes of the thermal output, making the system quite indifferent. However, at a high slope, even tiny alterations of the control signal will result in large changes of the thermal output, making the system sensitive and possibly unstable. To avoid instability problems, which effectively will ruin the control function, a low set value of the gain (corresponding to a wide P-band) is required in the controller. However, the result of a low controller gain is less control accuracy and slower response to disturbances. It is therefore crucial to avoid steep slopes of the circuit characteristic. In such perspective, the ambition should be to achieve a linear circuit characteristic since it will minimise the slope across the entire control range.

Circuit characteristic compound

The circuit characteristic consist of:

- Actuator characteristic
- Inherent valve characteristic
- Terminal characteristic
- Valve authority



The actuator characteristic shows the relationship between the incoming control signal from the controller to the actuator and the resulting valve lift. Usually, the characteristic is linear but for simple actuators, the characteristic curve may be quite unlinear.

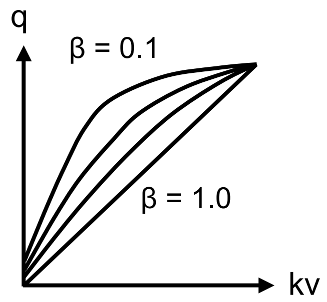
The inherent valve characteristic, which shows the relation between valve opening and valve capacity (kv value), depends solely on the mechanical design of the control valve. There are few different types of valve characteristics on the market; the most common ones are the *linear* and the *equal-percentage*, or actually *equal-percentage modified* (EQM) characteristics.

The terminal characteristic may vary a lot depending on design, size and temperatures but is definitely unlinear. A typical characteristic gives 50% power at 20% flow and 80% power at 50% flow, quite the opposite shape compared to an EQM valve characteristic. This is also the reason why EQM is usually preferred, when choosing control valve, since it counteract the unlinearity of the terminal.

Valve authority is a measure of the change in differential pressure across a control valve during operation. The flow through a control valve depends on the differential pressure across the valve and its kv value. The kv value is given by the inherent valve characteristic for any valve opening. If the differential pressure is constant during operation, the relationship between kv and water flow would be completely linear. However, in variable flow system, the differential pressure varies during operation, which means that the relationship becomes more or less unlinear. The "magnitude" of the unlinearity is expressed by the valve authority:

$$\beta = \frac{\Delta p \, V_{design}}{\Delta p \, V_{shut}}$$

β	=	*Valve authority [-]*
$\Delta p \, V_{design}$	=	*Differential pressure across fully open control valve at design flow [kPa]*
$\Delta p \, V_{shut}$	=	*Differential pressure across fully shut control valve [kPa]*



A high value of valve authority means that the differential pressure is close to constant and the relationship between kv value and water flow becomes quite linear. A low value, on the other hand, means that the differential pressure will increase much when the valve closes, resulting in large unlinearity between kv value and flow. The lower the valve authority is, the more unlinear the curve becomes.

Simply by looking at the compound of the circuit characteristic, it is quite clear that a low valve authority will make the circuit characteristic curve unfavourable. This is why the second condition must be fulfilled; too much variation in differential pressure across a control valve leads to low authority, distorted circuit characteristic and poor control. In addition, large variations in differential pressure will lead to interactivity between circuits, making control even more difficult.

Design and minimum valve authority

The available differential pressure across the hydronic circuit is transferred to the control valve once it shuts, which means that size, design and control of the system determines the differential pressure across the control valve fully shut (denominator in the expression above). Hence, the circumstance of the system at any given time determines the available differential pressure across the circuits, which means that the valve authority varies during operation. If, for instance, only one control valve shuts in a system while the others are fully open, the differential pressure across that specific valve will become significantly lower than if all control valves shut at the same time. This leads to two different definitions of valve authority; *design authority* and *minimum authority*. For two-way valves in variable flow systems, these definitions become as following:

$$\beta_{design} = \frac{\Delta p \ V_{design}}{\Delta H_{design}}$$

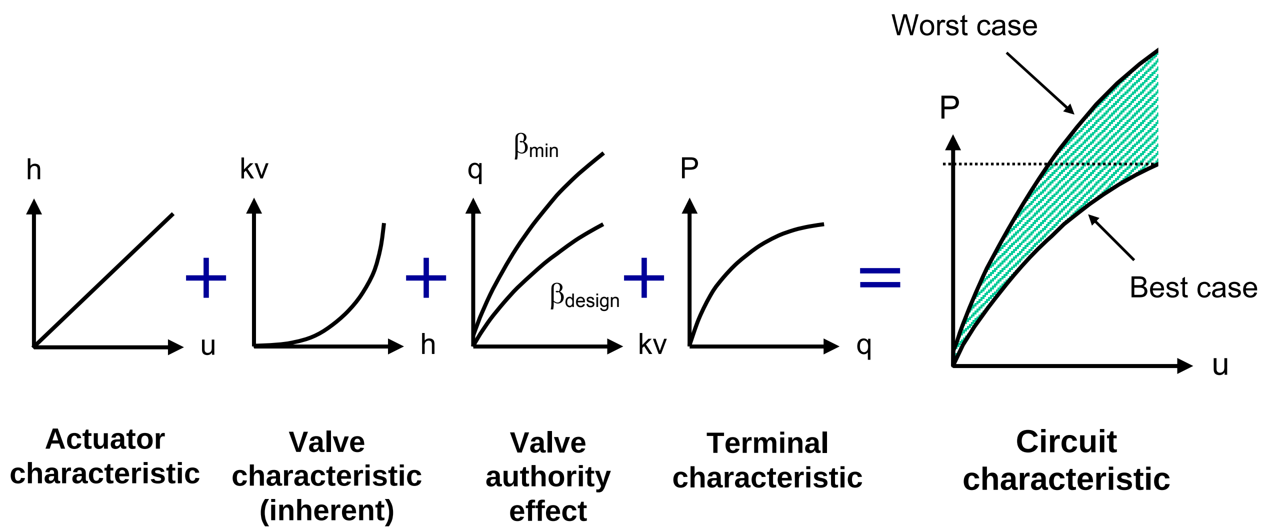
$$\beta_{min} = \frac{\Delta p \ V_{design}}{\Delta H_{max}}$$

β_{design} = *Valve authority at design condition [-]*
ΔH_{design} = *Available differential pressure across circuit at design condition [kPa]*

β_{min} = *Minimum valve authority [-]*
ΔH_{max} = *Maximum differential pressure across circuit during operation [kPa]*

Both the design and minimum authority definitions should be regarded when designing a system, since the level of the valve authority will vary somewhere between the design authority (highest possible level) and the minimum authority (lowest possible level) during operation.

The implication of varying valve authority on the circuit characteristic during operation is shown in the figure below. The best case represents the characteristic of the considered circuit for design authority, corresponding to a situation where all other control valves in the system are maintained fully open. The worst case, however, represents the circuit characteristic for minimum authority, corresponding effectively to a situation where all other control valves are maintained fully shut. The latter case results in much higher differential pressure across the circuit and, thus, steeper slope of the circuit characteristic and also substantial overflow when the control valve is fully open.



Hydronic design

The impact of the chosen control valve on the circuit characteristic and, hence, on the controllability of the system, is quite obvious since both the valve characteristic as well as the valve authority depends on the control valve selection. When choosing control valves both of these aspects must be taken care of.

- The design flow must be obtained for the control valve fully open in design conditions.
- In order to facilitate control, the valve characteristic should match the terminal unlinearity.
- To maintain a favourable circuit characteristic, the valve authority must not be too low.

In order to prevent the valve authority from distorting the circuit characteristic too much, the lowest values of design and minimum authority are:

$$\beta_{design} \geq 0.5$$

$$\beta_{min} \geq 0.25$$

The design authority for a control valve should not be less than 0.5, which effectively means that the design pressure drop through the fully open (two-way) control valve at design flow should at least be equal to half of the available differential pressure across the circuit at design condition. The purpose of this guideline is to make sure that the circuit characteristic at its best becomes quite close to linear, assuming that the inherent characteristic of the valve is appropriately chosen.

The second condition states that the minimum authority should not fall short of 0.25, which sets the lowest level of the circuit characteristic, when it is at its worst. Evidently, this condition is of much importance since it effectively settles the limit for the control to handle.

Besides choosing the control valves carefully, there are other design measures to implement in order to avoid low authority:

- Avoid large pipe pressure drops
- Use variable speed pumps
- Use Δp stabilization valves when needed

Even if the control valve is selected with great care, there might arise situations where the valve authority becomes too low anyway, simply because it depends not solely on the control valve sizing but on the design of the rest of the system as well. An effective measure in such perspective is to install differential pressure stabilization valves. These might improve the prerequisites for problem free control radically.

Conclusions

The objective of any HVAC plant is to provide a comfortable indoor climate whilst minimising costs and operational problems.
In theory, modern control technologies make this objective possible. In practise, however, not even the most sophisticated controllers perform as promised. The reason is often that the conditions necessary for good control are not fulfilled.
One such condition is that the differential pressure across control valves must not vary too much. The reason is to maintain the valve authority at a sufficient level in order to prevent the circuit characteristic from distorting too much and, thus, avoiding control problems.

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