Technical paper

Differential pressure controllers as a tool for optimization of heating systems

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If the differential pressure controller is not chosen correctly, you risk the following malfunctions:
1. The function does not live up to its intention
2. Bad functioning of the control equipment
3. Pressure oscillation in the system

A differential pressure controller can be chosen in different combinations, i.e. with or without flow limitation and with flow control.

To limit this size of this article only the subject differential pressure control is described here.

### Differential pressure controllers

#### Application

Differential pressure controllers are mainly used to create a constant differential pressure in a system independent of the variation of external pressure differential pressure in the supply net and consumption in the system as well. Differential pressure controllers also are very often used to create a hydraulic balance in a network.

The mostly used applications for differential pressure controllers are:
- Balancing control in secondary systems
- Control of differential pressure across district heating house substations
- Pressure and differential pressure control in district heating networks

#### Advantages in general

If differential pressure controllers are used in a subscriber station, a constant differential pressure across the substation in static relation can be maintained regardless of variations in the network differential pressure. This benefits end-users of the house substation as well as the utility company.

#### End-user advantages

Differential pressure controller chosen to control the differential pressure in a substation enables the exact sizing of the control valve. This again offers improved control conditions for the control valves, which gives the following advantages for the end-user:
- Stabilization of the temperature control. (Better valve authority and lower system gain).
- Low noise level and reduced risk of cavitation in the control valve
- Simple adjustment of the subscriber station
- Prolonged life of the control equipment

#### Utility company advantages

Use of differential pressure controllers in substations and in the district heating network will maintain a hydraulic balance in the network. This means:
- A good distribution of water in the supply network (satisfied consumers)
- The desired pressure level in the network can be achieved. Reduced risk of pressure oscillation in the network.
- The quantity of circulating water in the network can be limited (reduced costs for water circulation)
Control factors

This article describes the influence a differential pressure controller has on a well-functioning district heating house substation. This influence has a big impact on the above-mentioned advantages.

In order to provide a well-functioning system, knowledge of the following control factors is very important:

1. Valve sizing
   1.1. Sizing of a motorized control valve
   1.2. Sizing of a differential pressure controller
   1.3. Control ratio
   1.4. Performance ratio
2. Adjustment of the system
3. Noise in the control valve
4. Hydraulic balance in the supply network
   4.1. Flow limitation
   4.2. Accuracy of the flow limitation

1. Valve sizing

The correctly selected valve size is the basis of a stable temperature control of the heating as well as the domestic hot-water system.

1.1 Sizing of a motorized control valve

Imagine that you are going to size a control valve for a room heating system within a district heating system. The system is not equipped with a differential pressure controller see fig. 1.

The performance of the system is 220 kW.

With a temperature difference ΔT = 50 °C in the system, the flow rate in the system can be calculated as:

\[ Q = 1.05 \text{ l/sec} \approx (3.78 \text{ m}^3/\text{h}). \]

For the sizing of a control valve, the following equation for the \( k_v \) calculation is used

\[ k_v = \frac{Q}{\sqrt{\Delta P_v}} \]

\[ k_v = \text{capacity of the valve [m}^3/\text{h]} \]
\[ Q = \text{the needed flow rate through the valve [m}^3/\text{h]} \]
\[ \Delta P_v = \text{differential pressure across the valve [bar]} \]

Available min. expected \( \Delta P_{\text{supply}} \) in the network is:

100 kPa (1 bar)

\( \Delta P \) across other equipment is calculated as:

30 kPa (0.3 bar)

The flow rate is calculated on a basis of the performance of the system. The available differential pressure for the motorized control valve can be more difficult to determine because of the pressure variation in the network.

The differential pressure in the network can vary to such an extent that the available differential pressure for the control valve can be from 1 bar up to 5 bar.

At \( \Delta P_v = 0.7 \text{ bar} \) available for the valve, the calculated \( k_v \) value for the valve will be:

\[ \frac{3.78}{6.3} = 0.60 \text{ m}^3/\text{h} \]

A control valve of DN 25 mm with a \( k_{vs} = 6.3 \text{ m}^3/\text{h} \) will fit these conditions.

Available differential pressure for the control valve \( \Delta P_v \) is:

70 kPa (0.7 bar)

The \( d \Delta P_v \) needed for this valve can now be calculated:

\[ \Delta P_v = \left( \frac{Q}{k_v} \right)^2 = \text{bar} \]

\[ \Delta P_v = \left( \frac{3.78}{6.3} \right)^2 = 0.36 \text{ bar} \]

If the \( \Delta P \) in the network increases to 5 bar, the \( \Delta P \) available for the valve in the system is 500 − 30 = 470 kPa (4.7 bar) and then the needed \( k_v \) will only be:

\[ k_v = \frac{3.78}{4.7} = 1.74 \text{ m}^3/\text{h} \]

In this case a control valve of DN 15 mm with a \( k_{vs} = 2.5 \text{ m}^3/\text{h} \) has the sufficient capacity.

From the calculation it can be seen that the DN 25 valve under max. capacity and max. \( \Delta P \) will operate with

\[ \frac{k_{vs}}{k_v} = \frac{6.3}{1.74} = 3.6 \]

which is about one third of its max. capacity.

If the differential pressure of the system increases, the valve will start to close and operate on a lower part of the valve characteristic, see fig. 4.
1.2 Sizing of a differential pressure controller

If a differential pressure controller is chosen for the system, the valve calculation could be:

Available min. expected $\Delta P$ in the network is:
100 kPa (1 bar)

$\Delta P$ across other equipment is calculated to:
30 kPa (0.3 bar)

$\Delta P$ across the control valve:
30 kPa (0.3 bar)

Available differential pressure for the valve $\Delta P_V$ is:
40 kPa (0.4 bar)

Flow rate as control valve
3.78 m$^3$/h

Control valve:

$$k_v = \frac{3.78}{\sqrt{0.3}} = 6.9 \text{ m}^3/\text{h}$$

Selected valve: DN 32 $K_v = 10 \text{ m}^3/\text{h}$

$$\Delta P_v = \left(\frac{3.78}{10}\right)^2 = 0.14 \text{ bar}$$

The $\Delta P_v$ available for the differential pressure controller
100 ÷ 30 ÷ 14 = 56 kPa (0.56 bar)

$$k_v = \frac{3.78}{\sqrt{0.56}} = 5.05 \text{ m}^3/\text{h}$$

In this situation a differential pressure controller of DN 25 and a $k_v = 6.3 \text{ m}^3/\text{h}$ can be chosen.

At a max. $\Delta P$ in the system, the differential pressure controller will operate with:

$$\Delta P_v = 500 ÷ 30 ÷ 14 = 456 \text{ kPa (4.6 bar)}$$

$$k_v = \frac{3.78}{\sqrt{4.6}} = 1.76 \text{ m}^3/\text{h}$$

Fig. 3 illustrates that this valve will operate with an $X_p$ band of $\sim 5.9 \text{ kPa} \sim (0.059 \text{ bar})$ and that the control deviation will be from $\sim 5.9 \text{ kPa}$ down to 1.9 kPa. The total control deviation during the pressure variation from 1–5 bar will then be $5.9 – 1.9 = 4 \text{ kPa}$.

FIGURE 2: Control of a room heating system with a motorized control valve and a differential pressure controller

FIGURE 3: $X_p$ band and control deviation $X_p$ (kPa) of the Danfoss differential pressure controllers type APV

FIGURE 4: Valve opening related to the differential pressure in the system with and without differential pressure controller
Now we will observe that if variations in the network $\Delta P$ are from 100 to 500 kPa, the variation of the $\Delta P_v$ across the control valve in fig. 2 will only be $X_p = 4$ kPa. This means that if a differential pressure controller is installed in the system, it will almost keep the $\Delta P_v$ constant independent of the variation of the differential pressure in the network.

Fig. 4 shows you the ratio between the needed capacity ($k_V$) and $\Delta P$ supply in the network with and without a differential pressure controller. The lower the capacity ratio in a system without differential pressure controller, the higher the risk for oscillation due to operation below $k_{vr}$.

To avoid oscillation in a system, the following has to be taken into consideration:

- Setting of the parameters in the electronic controller
- Type of valve characteristics
- Control ratio of the valve

**Controller setting**
Setting of the control parameters in the electronic controller is very important to avoid oscillation. The setting can be simplified by selecting of a controller with functions such as auto tuning and motor protection [3].

**Valve characteristics**
A control valve must have characteristics adapted to the operating actuator and the heating application. For room heating system and domestic hot-water systems, a split characteristic will be the optimum choice (fig. 5).

The split characteristic is developed according to the heat exchanger efficiency typical for temperature sets used in district heating system applications [1] and [2].

1.3 Control ratio
The German recommendation VDI/VDE 2173 states the rules of defining the control ratio of a valve. The control ratio is here defined as the relationship between the $k_{vs}$ and the $k_{vr}$ value of the valve. The definition of the control ratio $R$ is:

$$ R = \frac{k_{vs}}{k_{vr}} $$

$k_{vs}$ is the max. capacity of a given control valve, $m^3/h$.

$k_{vr}$ is the lowest capacity of the valve at which the slope of control characteristic is within a given tolerance.

The text below explains that the higher a control ratio of a control valve, the better the control capability of the valve.

From the point on the valve characteristic (fig. 5) corresponding to $k_{vr}$ and down to the closing point, the slope of the characteristic is very step.

Therefore the gain in the control loop (flow rate/lift of the valve) will be relatively high. As a result, the temperature control in a heat exchanger system and a mixing loop might cause hunting of the controlled temperature at opening degrees of the valve below the values that correspond with $k_{vr}$.

This means that the capacity corresponding to the capacity at $k_{vr}$ normally is the lowest degree of opening at which a stable control can be expected.
Valves with a linear control ratio typically have a high control ratio, \( R = 100 – 200 \), whereas the typical control ratio of exponential and logarithmic valves is \( R = 30 – 50 \).

1.4 Performance ratio

The definition of the performance ratio can be expressed as the ratio between the max. performance \( P_{100} \) and the performance at \( k_v \), \( P_{k_v} \), at which there is a stable temperature control \( P_{100}/P_{k_v} \) (fig. 6).

The \( k_v \) of the valve at 100% load depends on the differential pressure across the valve. The higher the differential pressure, the lower the needed \( k_v \) value at \( P_{100} \) see fig. 4.

\( Q_{min} \) is according to the definition of the control ratio the lowest \( k_v \) value of the valve at which the controlled temperature can be expected to be stable.

If a differential pressure controller is used, the system can be set so that the valve operates with a \( k_v \) at \( P_{100} \).

For comfort reasons the temperature in a domestic hot-water system has to be very stable. If an instantaneous hot-water system is chosen, it has to be able to control a low capacity at a stable temperature.

A relevant demand to the lowest capacity in a domestic hot-water system is that the temperature should be kept stable if one person takes a shower. In this case the min. required capacity would then be keeping the temperature stable in connection with a shower and at the same time compensating for the heat loss due to the circulation of the domestic hot-water. A relevant capacity here depends on type of systems.

In two-step instantaneous system where in wintertime the cold water is preheated of the return flow from the room system, a relevant needed flow rate for after heat the domestic hot water, will be 0.20 \( m^3/h \). [4]. In parallel systems an equivalent capacity will be 0.33 \( m^3/h \).

From fig. 7 it can be seen that this system equipped with a \( \Delta P \) controller which can control this capacity. It also can be seen that the limit of \( \Delta P \), in a system without \( \Delta P \) controller is app.1 bar for two-step systems and 2.7 bar for parallel systems.

2. Adjustment of the system

Adjustment of a subscriber station ensures the highest possible degree of valve opening at 100% load.

If a differential pressure controller is used in a system, a final adjustment can be done in an easy and correct way.

A stable temperature control is achieved when the control valve operates in the entire range of valve characteristic.

This is the prior condition to gain full effect of the control ratio of the valve as the control ratio is calculated on the basis of the \( k_v \) value of the control valve.

Normally valves are sized by calculating the \( k_v \) value on the basis of the flow through the valve and a chosen pressure drop across the valve with due consideration to the valve authority.

Based on the calculated \( k_v \) value, a valve with a suitable \( k_v \) value is chosen, i.e. with a value which is often a bit higher than the calculated value.

The adjustment procedure is then to set the differential pressure controller at a lower differential pressure so that the control valves are fully open at 100% load. As it is often difficult to simulate a situation at 100% load, the setting pressure \( \Delta P \), can be calculated by means of the equation for \( \Delta P \), (equation 2).
3. Noise in the control valve

Noise in a control valve is very often generated if the differential pressure across the control valve is too high. If the system is not equipped with a differential pressure controller, the control valve very often will have to withstand the main part of the differential pressure in the network. This can generate noise in the system.

Typical type of noise categories from control valves with high ΔPv is:
1. Flow noise
2. Mechanical noise
3. Cavitation

The mentioned noise categories can be unacceptable.

Category 1 – 2 depend on the type of valves, design and their sizing. Category 3 depends on the type and design of the valve.

Cavitation result in bubbles imploding in the valve, and this sounds like hammering. Cavitation very much depends on the differential pressure across the valve and the level of pressure (static and pump pressure), and temperature in the valve.

If the pressure condition around the valve and the water temperature is known, the Z value can be calculated

\[ Z = \frac{P_s - P_2}{P_1 - P_s} \] (4)

P1 is the pressure level at the inlet the valve.
P2 is the pressure level at the outlet of the valve.
Ps is the vapor pressure at the corresponding water temperature.

As illustrated in fig. 8 the cavitation very much depend of the differential pressure in the system and the pressure level. The cavitation factor of a control valve normally is between 0.5 – 0.6 depending of dimension of the valve.

A differential pressure controller can be used for selection of the pressure level in the motorized control valve as well as for reduction of the differential pressure across the valve and thereby elimination of the noise in the valve.

4. Hydraulic balance in the supply network

A district heating system is in hydraulic balance when the water flow to the individual consumers is exactly what they need for room heating and hot water preparation. If a system is not in hydraulic balance, there could be the following reasons:
• Oversized control valves
• The consumption is not according to specification
• No possibility of adjusting the flow range
• The system has not been adjusted

According to the specification, hydraulic balance means limitation of the flow range in a system to a flow rate corresponding to real consumption.

4.1 Flow limitation

Differential pressure controllers in a substation can be used as flow limiters. The setting of the differential pressure controller can be calculated by using equation 2.

\[ \Delta P_{set} = \left( \frac{Q_{\text{max}}}{k_v} \right)^2 \text{ bar} \] (5)

\[ \Delta P_{set} = \text{the setting of the differential pressure controller.} \]

\[ Q_{\text{max}} = \text{Flow rate in the station at 100\% load.} \]

\[ k_v = \text{value of the unit in the control loop of the differential controller.} \]

This means the part of the substation between the points where the impulse tubes are connected. If the differential pressure controller only controls one valve (see fig. 2), the \( k_v \) value of the valve is to be used.

Under precondition that the differential pressure controllers are used in substations and that they are adjusted according to the needed max. flow rate, they will establish a hydraulic balance in the network. This means that the flow rate in the substation is limited according to the max. adjusted flow rate.

4.2 Accuracy of the flow limitation

The expected accuracy of the flow limitation depends on the pressure variation in the part of the system between the points where the impulse tubes are connected.

As a differential pressure controller is a proportional controller, the pressure variation that can be seen will be the change in the controller’s control deviation \( \Delta X_p \) during variations in the differential pressure in the supply net.

The accuracy in the flow variation \( \Delta Q \) can be calculated. \( \Delta Q \) at increased differential pressure in the net will be:

\[ \Delta Q = Q_1 - Q_2 \]

\[ \Delta Q = Q_1 - k_v \times \sqrt{\Delta P_{set} - \Delta X_p} \]
Conclusion

The application of differential controllers in a subscriber station is the most important step to comply with the above-mentioned conditions. In other words, the differential controller ensures a well-adjusted system. In this way it is possible to ensure the best control performance with a stable temperature control, a high performance ratio and a noiseless system.

A well-adjusted system also is an important part of a district heating network where a hydraulic balance is of high importunes. A well-adjusted system means a limitation of the flow rate to max. consumption – a differential pressure controller is a simple tool for this purpose.

\[ \Delta Q = Q_1 - \frac{Q_1}{\sqrt{\Delta P_{set}}} \times \sqrt{\Delta P_{set} - \Delta X_p} \]

\[ \frac{\Delta Q}{Q_1} = 1 \times \frac{\sqrt{\Delta P_{set} - \Delta X_p}}{\sqrt{\Delta P_{set}}} \]

From the calculation it can be seen that the flow variation \( \Delta Q/Q_1 \) depends on \( \Delta P_{set} \) and \( \Delta X_p \). (See fig. 8).

Fig. 9 shows you the calculated accuracy of the flow limitation if a differential pressure controller is used as flow limiter. The accuracy is higher at the increased controlled differential pressure \( \Delta p_{set} \).

Operating with lower \( X_p \) can increase the accuracy of the flow limitation. However, the lower the \( X_p \), the larger the dimensions of differential pressure controllers. Here it has to be taken into consideration that the lower the \( X_p \), the higher the risk of oscillation in the differential pressure controller.
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[4] Herman Boysen, *District heating substations and selection of regulating valves; News from DBDH (Danish board of District Heating) 2/1999*

More articles

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