

ENGINEERING TOMORROW

Article

How to avoid pressure oscillations in district heating systems

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The phenomenon pressure oscillation in District Heating systems can arise even in traditional systems with normal supply conditions. Over years the reason and theories for it has been discussed and many remedies has been proposed to eliminate or reduce the oscillations.

Introduction

Pressure oscillation can be observed in the whole network, part of it or in the District Heating house substation.

Experience shows, that high concentration of substations in an area gives increasing risk of pressure oscillation (Resonance oscillation). In one family house areas, where the concentration of small district heating substation is high, this is very typical. Differential pressure controllers play a significant role in this phenomenon. Also the internal system can be the source for oscillation (Self-oscillation). A correct valve and system sizing, right chosen application and correct installation of the differential pressure controller can avoid this kind of oscillations.

This conclusions mentioned, are based on detailed analyse of the phenomenon where the following tools have been used:

- Observations in the field.
- System calculation.
- Computer simulations.
- Laboratory tests for verifying the theory's.

Among others, pressure oscillation in district heating network can have the following negative effect:

- Generation of noise in the system.
- Instable temperature and pressure control.
- Failure of components in the application caused by peak loads and/or fatigue.

This article describes a part of the experiences gained by Danfoss in this particular field of application knowledge. The article also includes a brief description of the theoretical and practical background work made. The contents are:

- Differential Pressure Controller function.
- Influence of application layout and sizing.
- Types of oscillations and recommendations on how to damp the oscillations.
- Computer Simulation Model.
- Laboratory Test Rig.
- Conclusion.

Differential Pressure Controller function

The task of the differential pressure controller is to keep the system differential pressure in a control loop on a constant value, expressed by

$\Delta p_a = p_1 - p_2$

The main parts of the differential pressure controller are the control valve, a diaphragm house, a setting spring and two impulse tubes.

 p_1 and p_2 are the pressures where the two impulse tubes are connected to the system. The impulse line for determination of p_1 and p_2 can be connected across at the whole system where more heat circuit are connected, or it can be connected across a control valve for controlling a single loop. See fig 1.

To understand the function of the differential pressure controlling it is important to realize that only the pressure where the differential pressure controller is mounted can be controlled or adjusted. The pressure in the connected supply lines are only used as a reference for the controlled differential pressure.

The function of the differential pressure controller is based on a force balance established in the controller, between the spring and the differential pressure in the impulse tube.

The mode of operation in a differential pressure controller is as following: During operation, the differential pressure controller will try to find a force balance where the force from the setting spring Fsp together with the lower pressure p_2 will find a balance with the higher pressure p_1 .



A = area of the diaphragm in the differential pressure controller [m²].

This shows that the force balance and the valve cone will move to another position under the following circumstances:

- \bullet Change in the Δp_{a} because change in heat consumption.
- Change of pressures in the distribution net.





FIGURE 1: dP control of single loop and dP control of several loops

 \bullet Change of the Δp_{a} by adjusting the spring setpoint.

A movement of the valve cone means change of Δp_a across the differential pressure controller diaphragm.

The reaction speed of the differential pressure controller R_{h} can be expressed as:

$$R_{h} = q_{i} \times \frac{\Delta k_{v}}{\Delta s} \times \frac{1}{A_{m}} [m^{3}/h \cdot \sqrt{bar/sec}]$$
 (2)

Where

 $R_{\rm h}$ = reaction speed of the differential controller

 $q_i = flow rate in impulse tube [m³/sec]$

 $\frac{\Delta k_v}{\Delta s} = valve \text{ gain characteristic} \\ [m^3/h \sqrt{bar/m}]$

 A_m = Area of the diaphragm in the pressure controller [m²]



FIGURE 2: Cross-section of differential pressure controller, principal

In general it's a fact, that a too quick reacting differential pressure controller (high R_h value) can generate oscillation in a system. A lower R_h will reduce the system tendency for oscillation.

As the formula (2) indicates, the only way to change the R_h value in an existing system, is to change the flow rate in the impulse tube. It can also be seen from formula (2) that a oversized valve, normally resulting in a high d_{kv}/ds value, will increase the risk of oscillation.

Influence from application layout and sizing

System elasticy

All water-contained equipment in a heating system has more or less elasticity. This means, if the pressure in a system changes, the amount of water trapped in the system will change too. Not all components have the same range of elasticity. Heat exchangers and radiators have a high rate of elasticity. Compared to this, the elasticity of valves and pipes can be considered as insignificant.

Air in the water has significant influence on the system elasticity.

At increasing pressure, more water will be pressed into the system. On the other hand at pressure decreasing, water will be pressed out of the system because of the system elasticity. The relation between changes in pressure Δp_r and changes in trapped volume of water V is determined by the system elasticity. The definition of system elasticity C [m³/Pa] is the relation of volume change of water in the system related to the pressure change:



The rate of system elasticity can easily be measured in an individual loop. The procedure is:

Close the main shot-of valves in the loop where to measure the elasticity. Open a drain in the loop and measure the volume of water drained out until the pressure has dropped e.g. 1 bar.

System type, in DK and S	System elasticity
	C [ml/Bar]
New 1-family installations	30-50
Old 1-family installations	50-100

Table 1: Typical system elasticy's in district heating substations with Heating and DHW circuit



Dimension of the supply lines

In district heating systems, the size of the supply lines have an essential influence on creating pressure oscillation. Velocities of water in a pipeline depend on the differential pressure and the length and the dimension of the pipe.

Changing velocity of the water stream in the system, will generate a pressure pulse positive or negative due to acceleration or deceleration of the water.

The task of the differential pressure controller is to maintain a set Δp_a . During operation the pressure in the system determines whether a large or small quantity of water is let into the system (when the controller is installed in the flow pipe) or whether more or less water is remaining in the system (when the controller is installed in the return pipe) in the way that the quantity of water necessary to give the set differential pressure is always present in the system. Variations in pr cause variations in the amount of water in the system because of the system elasticity. This change of amount of water in the system during variation of p_r can generate a change in velocity for the water stream and consequently high pressure surge on which the differential pressure controller can "overreact" and generate oscillation.

Assuming that the compressibility of the water is insignificant and ignoring pipe elasticity, the amplitude of a pressure surge Δp_d [kPa] (index d for dynamic) can be evaluated by means of equations:

$$\Delta p_{d} = \frac{\Delta q}{\Delta t} \times \frac{L}{\frac{\pi \Delta D^{2}}{4}} \times \rho \text{ or } \Delta p_{d} = \frac{\Delta u}{\Delta t} \times L \times \rho \text{ [kPa]}$$

where

- ρ = the density of the water [kg/m³]
- q = specific flow rate [m³/s]
- u = flow velocity [m/s]
- t = time [sec]
- L = length of the pipe [m]
- D = Internal pipe diameter [m]

As the cross-sectional area of the pipe is a function of the square of the inner diameter of the pipe (D), it can be seen that the diameter of the pipe has a big influence of the Δp_d . Also the length of the pipe has influence of Δp_d .

The dimension of the supply line is very often kept small. The reason are:

- Heat loss from the pipeline.
- Pipeline cost price.
- Installation cost price.



FIGURE 3: The four general applications including differential pressure controller

(5)

Position of the differential pressure controller

To avoid the impact of system elasticity it's important that the impulse tubes for determining the controlled pressure are connected in a non-elastic part of the system. Normally in line with a temperature control valve as shown in fig. 3 b) and d). If the impulse tube, determining the controlled pressure, is connected in the elastic part of the system, fig 3 a) and c), the conditions for oscillation possibly are present.

Taking the compression of the water into consideration, the amplitude of pressure surge Δp_d , when changing the water velocity Δu is:

 $\Delta p_{d} = \Delta u \times a \times \rho$

where

a = sound-progagation velocity in water [m/s]

Depending on the air content in the water, the speed of sound normally ranges between 1200 –1400 m/s. Air content in the water will drastically reduce the speed of sound and there by also the pressure peak. If the content of air in the water is 0,7%, the speed drops to 250 m/sec.

Types of oscillations and recommendations on how to damp them.

Pressure oscillation can be split up in two main categories.

- Reaction oscillations.
- Self–oscillation.

Resonance oscillation

Reaction oscillation, as it can be seen in a system, can start when the differential pressure controller reacts and reinforce a pressure change entered from the network. The controller itself is not unstable, but it only reacts on the impulse coming from the network.

A typical source for resonance oscillation can come up when more differential pressure controllers within a short distance are creating self– –oscillation. Typical for this behavior is the differential pressure in a residential house area with high content of air in the water. Here the differential pressure controller's act simultaneous as one big differential pressure controller, as the time constant is the same all over in the system. This cause rapidly changes in acceleration or deceleration in the network.

Even though most of the individual differential pressure controllers in a system are stable and in balance, the resonance oscillation coming from outside will influence the differential pressure controllers and it can be considered as all systems operate unstable.

How to recognize the resonance oscillation?

Characteristics of resonance oscillation are:

- Strong pressure oscillations in flow- and return line.
- Pulsating noise or flow noise altering with silence.
- Oscillation frequency between 0,5 Hz and 0,1 Hz.
- The oscillation disappear after a while when the system is well vented.

- The oscillation is not regular, i.e. periodically stationary.
- The pressure peak is different from case to case.

How to reduce resonance oscillation?

Activity to reduce resonance oscillation in a system:

- Make sure the system is well air vented.
- Install the differential pressure controller in a loop with low rate of elasticity. (i.e. next to and in series with the control valve).
- Damping of the differential pressure controllers on all or on some of the locations in the affected area.

One way of damping the differential pressure controller could be increasing of the resistance in the impulse tube, by applying longer impulse tubes and/ or decrease the internal diameter.

Have in mind that the consequence of damping of the differential pressure controller will lead to slower control of the system. This can be critical in systems with instantaneous heat exchangers in Domestic Hot Water systems. Figure 4 shows the result of a quick change of the pressure. If the net pressure drops momentary, and the reaction speed (Rh) on the differential pressure controller is very slow, there is a risk of negative Δpa . This results in backwards flow through the system, and may cause "hammering" control valves. See the dotted area (a) in figure 4, representing the period of negative system differential pressure.

Self-oscillation

Self-oscillation occurs in individual systems and starts when the differential pressure during operation reacts on pressure impulse generated within the system loop of the system. In this case the differential pressure controller is an essential part of the phenomenon.

Parameters that influence the oscillation can be:

- The function of the differential pressure controller.
- The reaction speed of the differential pressure controller.
- The system elasticity.
- The dimension of the supply lines.
- Typical for self-oscillation is:
- The pressure controller is able to change the flow rate faster than the flow rate in the pipe can be changed.



FIGURE 4: Consequence of a momentary change in the net pressure



FIGURE 5: A system with self-oscillation (a). The same system after damping the impulse pipes (b)

- The system elasticity in the control loop for the differential pressure controller must be large enough to create a pressure oscillation.
- Critical for this kind of oscillation is:
- \bullet System elasticity in the control loop. \bullet The reaction speed $R_{\rm h}$ on the
- differential pressure controller. • The dimension of the District Heating
- supply lines.
- A change in system pressure can be the trigger for oscillation, because the controller is not stable.

How to recognize the selfoscillation?

The following conditions are characteristic for self-oscillation:

- Strong pressure oscillation in the flow and return line during operation. This will disappear when the system is shut off.
- Pulsating noise or rumbling altering into silence over and over.
- Oscillating frequency between 0.2 Hz and 3 Hz.

How to reduce self-oscillation?

Activity to reduced or eliminate self-oscillation.

- Dampen the differential pressure controller impulse tubes.
- Install the differential pressure controller in the stiff part of the application.
- If the differential pressure controller is mounted in the flow line, it has to be ensured that the static pressure in the system is high enough to vent it.

Simulation model

To investigate the influence of the application layout and sizing of i.e. consumer's branch lines, on the overall hydraulic stability, and in order to develop design rules for future installations, a simplified dynamic model of a consumer substation was built. The model is universal as regards number and placements of pipes and valves, as long as they are connected in series. The model is build up in Simulink[®], which is a widely used software for i.e. dynamic control system simulations and analysis. The model is build up by sub systems as described below.

Pipes

The dynamic pipe model is of the "rigid water column type", where the fluid flowing through the pipe is treated as a single mass moving at the flow velocity U. This assumption is applicable if the elasticity of the system is dominant, compared to the compressibility of the water in the branch lines. The mass is accelerated according to the net pressure forces acting at the pipe ends as well as the pressure head loss due to friction in the pipe. The model considers the water to be incompressible, and it takes the pressure drop due to friction into account as well as pressure variations due to acceleration/deceleration of the water. The steady state flow velocity is obtained when the pressure loss across the pipe equals the difference in pressures at the pipe ends.

The pressure difference between the pipe ends Δp_{p} , thus constitutes three parts: The flow friction forces Δp_{f} , the minor loss pressure (bends, flow meter, strainer etc.) Δp_{m} , and the dynamic pressure variations Δp_{d} .

The calculation of Δp_f and Δp_m is straight–forward and is based on the well–known principles of flow theory:



FIGURE 6: The Simulink[®] model of application (a) shown in figure 3. The lines between the model components represent data connections



FIGURE 7: Experimental and simulation results using an APV controller

$$\Delta p_{m} = \zeta \times \frac{\rho \times u^{2}}{2}$$
 (6)

where ζ is the minor loss coefficient, and

$$\Delta p_{f} = \frac{\rho \times u^{2}}{2} \times \frac{f \times I}{d}$$
 (7)

where f is the friction factor and d the pipe diameter.

 Δp_d can be calculated on the basis of Newton's second law, the momentum equation:

$$\Delta p_{d} \times A = m \times \dot{u}$$
 (8)

where m is the lumped mass and u denotes the time derivative of the flow velocity. Equation (8) implies that

$$\Delta p_{d} = A \times I \times \rho \times \dot{u} \times \frac{1}{A} = \dot{u} \times I \times \rho$$
 (9)

The total pressure difference across the pipe is then:

$$\Delta p_{\rho} = \Delta p_{m} + \Delta p_{f} + \Delta p_{d} = \left[\frac{u^{2}}{2} \times \left[\zeta \frac{f \times I}{d}\right] + \dot{u} \times I\right] \times \rho$$
(10)

As it can be seen from equation 5, the differential equation in of the non–linear type.

Valves

The flow q through a valve is a function of the actual valve opening s and the pressure drop Δp_v across the valve. The well-known static orifice law models the flow: $q = k_v \times \sqrt{\Delta p_v}; k_v = f(s)$

In this case, the sign of the pressure loss and flow is of relevance. Equation (6) is now expressed as:

$$\Delta p_{v} = \left[\frac{q}{k_{v}}\right]^{2} \operatorname{sign}(q)$$
 (12)

Elastic part

The elastic part of the model is characterised by a lumped pure air elasticity. Effects from the elasticity of pipes and radiators are included in the specification of the system elasticity, but described by pure air volume behaviour, which is a reasonable assumption in the case where the dominant elasticity is represented by the air volume. The ideal gas equation for the air volume, based on constant temperature, is:

$$p_0 V_0 = k$$
 (13)

Deriving the elasticity from equation (13) becomes:

$$\frac{\partial V}{\partial p} = -k \frac{l}{p^2}$$
(14)

As it can been seen from equation (14), the elasticity for the pure air volume is depending on the static pressure, p, i.e. a double up of the static pressure results in 4 times lower elasticity. For small changes in static pressure a linearization can be done, which results in the expression:



where q_1 and q_2 are flow into and flow out of the lumped system described by the elasticity C. This is a reasonable description of the pipes and heat exchanger, which to a certain extent have linear elastic characteristics. If equation (15) is rearranged, an expresion to determine the system pressure pr is determined by:

$$\dot{p}_r = (q_1 - q_2) \frac{l}{C}$$
 (15)

Controller activating unit

The correct dynamic description of the activating unit of the differential pressure controller is of great importance, and at the same time it is the most complicated part of the simulation model. Several different factors and variables have to be accounted for. Due to the complexity, the exact formulation of the applied model will not be listed here, but in principle the time derivative of the valve opening s. can be determined by means of

 $\dot{s} = f(\epsilon, A_m, R_i, H, b, c, f_o), \epsilon = \Delta p_{set} - \Delta p$ (16)

where Δp denotes the controlled differential pressure, ϵ is the control error, Am is the diaphragm area, R_i is the flow resistance in the impulse tubes,

H is the hysteresis width, b is a damping constant, c denotes the spring constant and F0 is the pretension of the spring (determines the set point of the differential pressure controller).'

The system model

The next step is to put together the sub systems, based on the above stated equations, and a network pressure equation, to form a dynamic, nonlinear simulation model. By this, a tool for describing the dynamic function of the differential pressure controller, including flow and pressure variations in the substation, is launched. The *Simulink*[®] block diagram model of the application (a) from figure 3 is presented in figure 6.

The simulation model described in this section has been thoroughly verified by the comparison with measurements from field tests as well as measurements obtained through tests on a laboratory test rig. The test rig was designed especially with the purpose of verifying the knowledge and theories explored through the simulations.

It was found that the model in all configurations gives a good qualitative description of the relations and processes involved in the dynamics of the differential pressure control. As long as the elasticity of the substation is of reasonable size and thereby dominates the dynamics of the system, then the quantitative results are quite accurate. A comparison of measured



FIGURE 8: Calculated accuracy of the flow limitation if a differential pressure controller is used as flow limiter. The accuray is higher at the increased differential pressure Δp_{set}

and simulated pressures after a Danfoss APV pressure controller for configuration (a) in figure 3 is illustrated in figure 7.

Laboratory test rig

The build up test rig is equipped with variable service pipe diameters (13 mm and 20 mm) and variable lengths (2 m, 10 m, 20 m and 40 m). A water tank equipped with level indicator and pressure gage introduces the system elasticity. Hereby, the elasticity of the pure air volume can easily be calculated. If the influence of i.e. the heat exchanger or the water compressibility are of relevance, the elasticity can simply be measured as described above. The test rig is equipped with flow- and return mounted differential pressure controllers and a number of control valves. This gives the option easily to switch between the four different applications as shown in figure 3. A real time data acquisition system is logging the measured pressure values. Furthere more the pressure levels are plotted currently in real time on a display.

Conclusion

This paper explains the nature of differential pressure controller in relation to oscillation. Some operative hints for eliminating or reducing pressure oscillations are presented. Thanks to the application knowledge in the field of differential pressure control, it is now possible to solve pressure oscillatory problems in already existing applications, and to offer specific advice regarding the right design of new applications in order to eliminate the risk of pressure oscillations. In the future, when new applications are designed, allowances should be made for the problems that arise from the interrelationship between system elasticity in the control loop, the control speed of the pressure controller, and the dimensions of the consumer service lines. The aim should be to make the elasticity in the control loop of the pressure controller as low as possible, and at the same time to avoid too small diameters of the branch lines. In practice, it has already been observed that the whole district heating network becomes more stable when the experience described in this article is incorporated into the design of consumer installations.





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