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Article

Optimum **control of heat exchangers**

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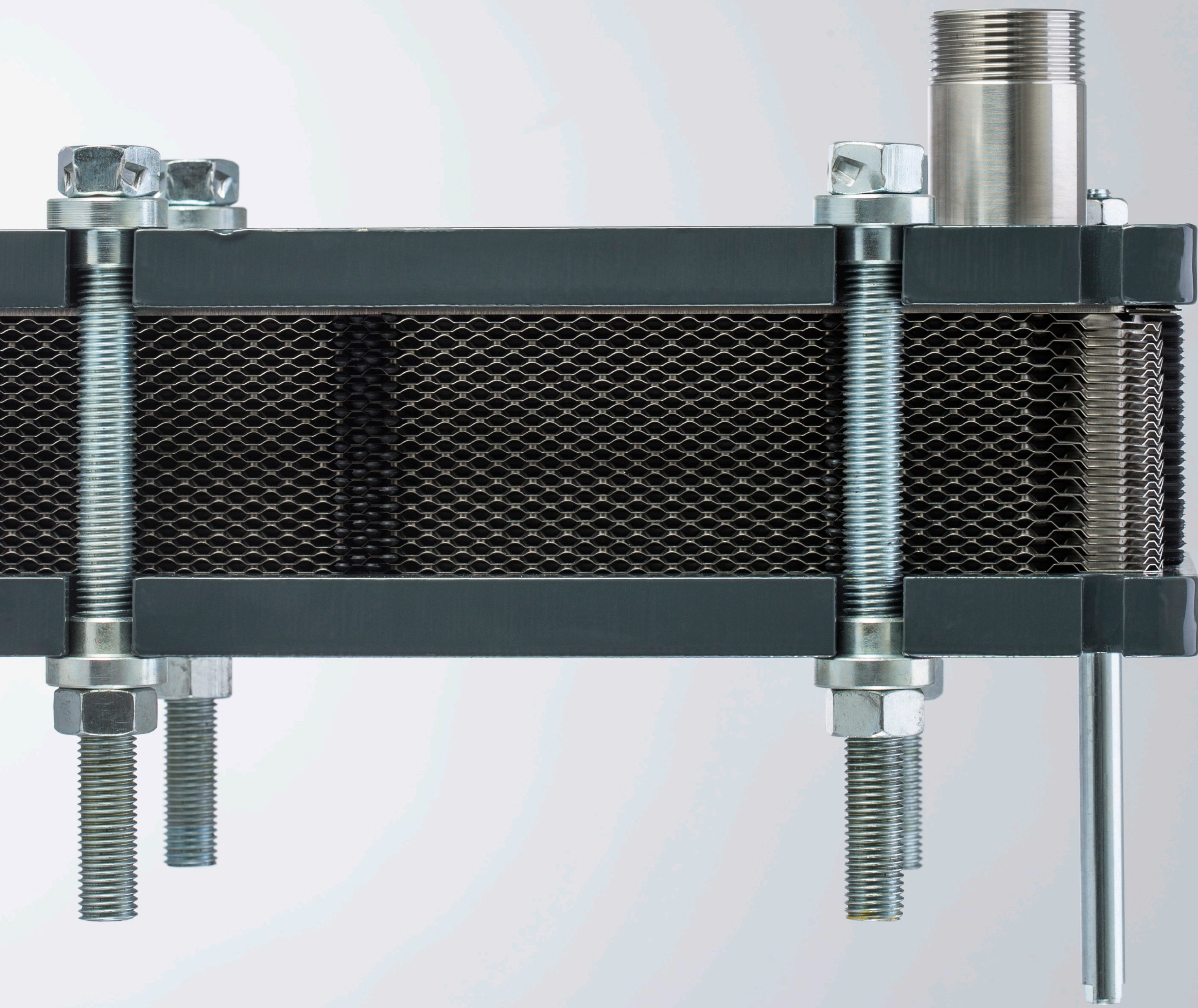

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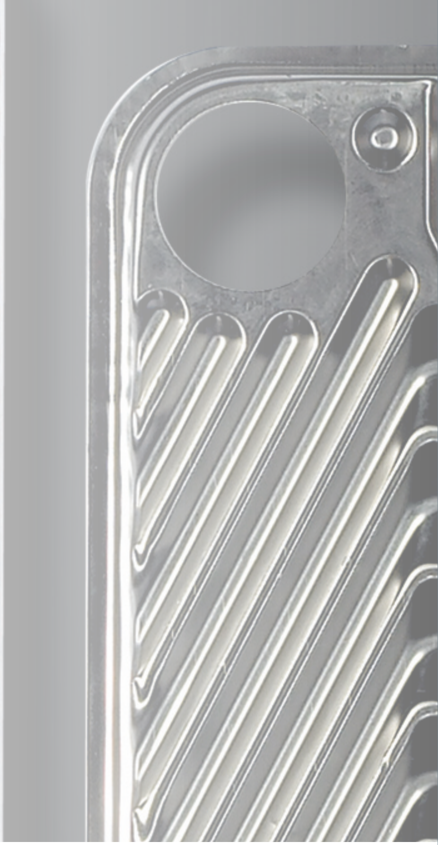


Optimum control of heat exchangers

An analysis of the common theory and an example on control development.

The present paper concerns the control of high-performance heat exchangers for hot water service. Some of the basic control theories and their decisively important relationships are analysed from a theoretical point of view. A newly developed control is described, putting the various elements in the design into the perspective of control theory.

1. Introduction

It has become increasingly common for hot-water service from district heating systems to be heated in high-performance heat exchangers with no form of hot water storage. One reason is the simple, compact equipment required; another is that the instantaneous heating principle enables highly efficient cooling of the district heating water: a very important consideration in modern district heating systems based on combined heat and powergeneration.

Concurrently with the increase in application, and the increase in requirements on the cooling of district heating water and the quality of control (e.g. temperature stability of service hot water), greater attention is being focused on control system performance. This topic has been the subject of several research projects in recent years. Since the instantaneous heating principle is gaining ground not least among small-scale systems (e.g. single family houses) where the cost of the installation may be decisive in relation to the competitiveness of district heating compared to other methods of heating, more and more attention is also being paid to the financial aspect. Since higher performance is being demanded at the same time as the economic factors are becoming increasingly important, it is vital that all work on the development and/or choice of control systems should be based on a thorough understanding of the characteristics of control problems, in that such an understanding is a prerequisite for the development of control systems which are optimum from both technical and economic points of view.

FIGURE 1: Self-acting control valve for small hot water service heat exchangers

It is unfortunate that some of the literature dealing specifically with the regulation of heat exchangers confuses some of the more basic relationships within control technology and inadequate assumptions are made. The first part of this article therefore discusses certain central aspects of the static characteristics of control systems which need stressing. The remainder of the article briefly describes the development of a new, self-acting control valve for hot-water service heat exchangers, see fig. 1, in which the various elements of control technology are set in relationship to the principles dicussed in the first part.

2. Static characteristics

Most of the papers and articles written on the regulation of heat exchangers take it as a basic assumption that the precondition for satisfactory control should be an attempt to achieve a load-linear regulating loop. The term „load-linear regulating loop" means that there is a linear relationship between the position of the control valve and the heat transferred. Heat exchangers are also frequently referred to as non-linear, since there is a non-linear relationship between the flow on the primary side and the heat transferred. These two assumptions generally lead to

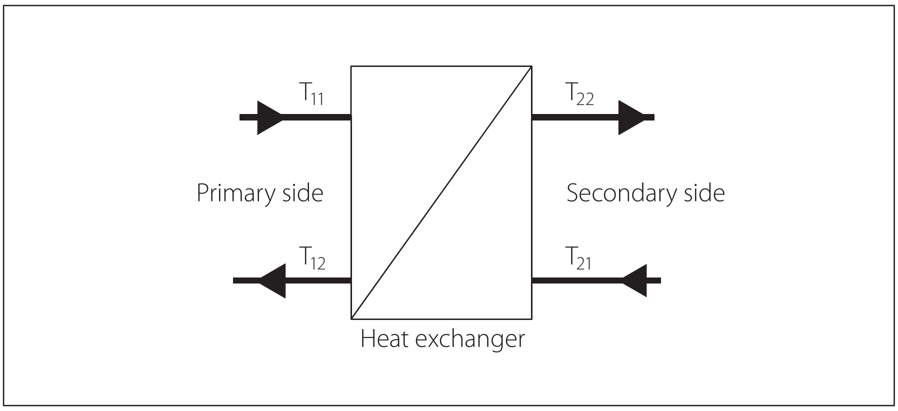


FIGURE 2: Heat exchanger

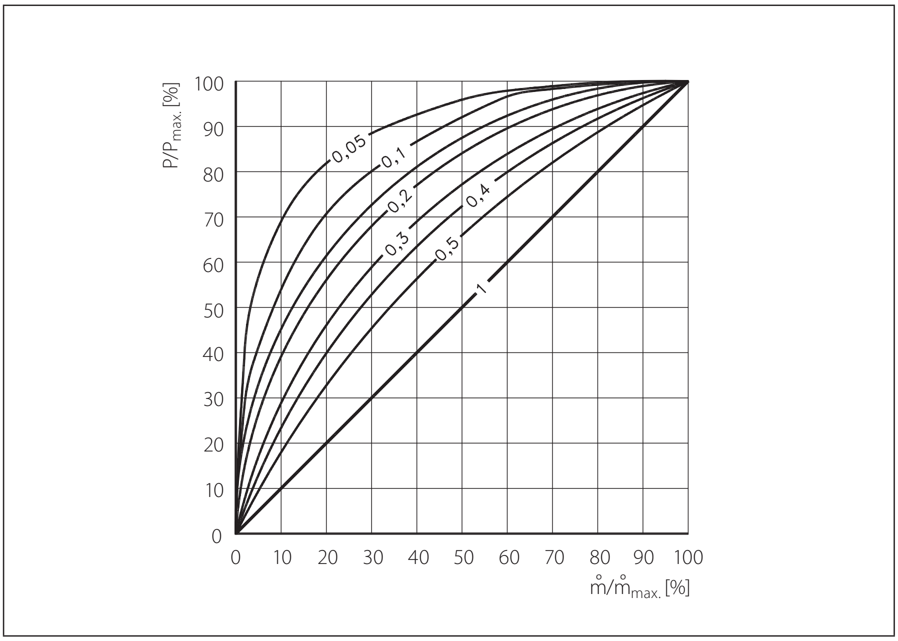


FIGURE 3: Static characteristic of heat exchanger showing ht1 from 0.05 - 1

the conclusion that valves with quadratic or exponential characteristic curves ought to be used to counteract the non-linearity of the heat exchanger, thus achieving the desired load linearity. Neither the assumption of an optimum result of the load-linear regulating loop nor that of which valve characteristics are the right ones for achieving such linearity apply in all circumstances. Under the conditions generally prevailing in district heating substations, the logic leaves something to be desired, as discussed below.

2.1 The load - linear control loop

As stated in the literature, there is in principle a non-linear relationship between the regulated (primary) flow and the heat transferred, e.g. Hjorthol (1990). How non-linear the overall characteristics of the heat exchanger are in practice however depends entirely on its capacity. The static characteristics of the heat exchanger depend on the temperature efficiency of the primary side. The temperature efficiency, ht1, specifies the relationship between the maximum temperature difference and the cooling: see eqn.1 and fig. 2.

$$\eta_{t1} = \frac{T_{11} - T_{12}}{T_{11} - T_{21}} \qquad (1)$$

where

T11 = supply temperature on the district heating side,

T12 = temperature of return to the district heating mains, and

T21 = secondary side inlet temperature

In fig. 3 we see what the static characteristics look like at various levels of temperature efficiency (x axis = percentage flow; y axis = percentage heat transferred). The degree of efficiency depends on the capacity. The characteristic curve of an over-sized heat exchanger will be more linear than that of an undersized one.

As can be seen, for ht1 in the 0.5 to 1 range, the characteristic curve is only slightly non-linear.

In Sweden, Norway and Germany the following sets of temperatures are quoted for hot-water service heat exchangers —>

	Primary side T11/t12	Secondary side T21/T22	
Sweden	65/25	5/50	Värmeverksföreningen 1994: (District Heating Association,
Norway	80/30	5/55	(Hjorthol (1990))
Germany	70/40	15/50	(Manthey (1992))

The degrees of temperature efficiency at the above sets of temperatures are:
Sweden: $h_{t1} = 0.67$
Norway: $h_{t1} = 0.67$
Germany: $h_{t1} = 0.55$

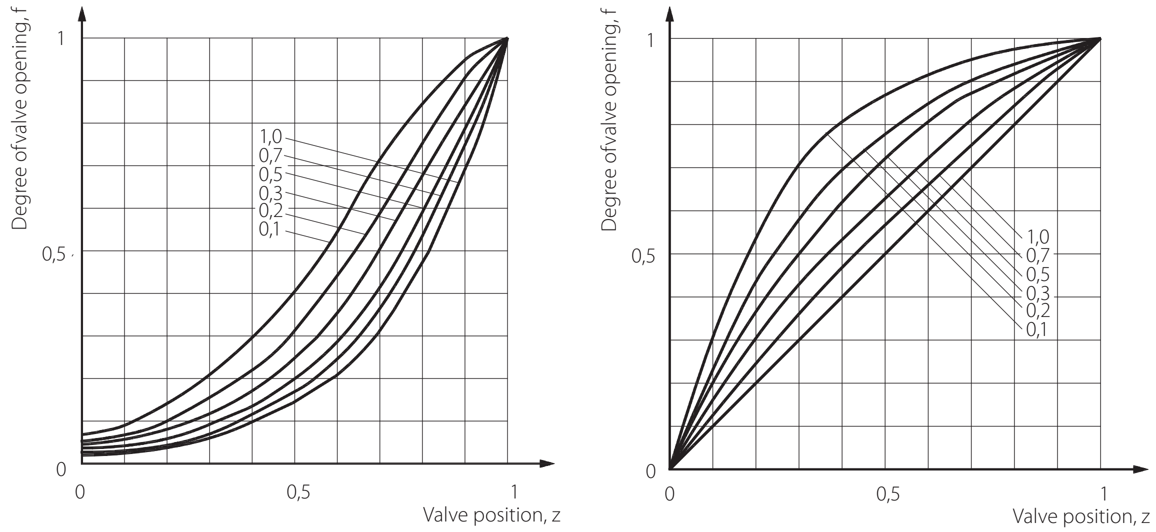


Fig. 4a. Effective valve characteristic - exponential characteristic with authority range 0.1 to 1.

Fig. 4b. Effective valve characteristic - linear characteristic with authority range 0.1 to 1.

FIGURE 4

It must be assumed that the sizing cases represent the highest demands placed on the heat exchanger (highest load at lowest flow temperature), and that temperature efficiency would be higher in other situations. In addition, a size of heat exchanger would always be selected to be „on the safe side“ so that temperature efficiency would be higher still.

Fig. 4 shows how their authority influences the effective characteristic curves of valves with linear and exponential characteristics. As can be seen, provided their authority is above 0.5, the effective characteristics are very close to the real characteristics,even in valves not equipped with a differential pressure control.

Thus, the assumption that the characteristics of heat exchangers are highly non-linear is in fact wrong when FIGURE 4 applied to water/water exchangers in district heating installations built to fulfil modern sizing standards (cooling requirements). Starting from the set of temperatures used for sizing hot-water service heat exchangers in Sweden, simulation models (see Ch. 3.1) were used to calculate what the valve characteristics ought to be in the event of full linearity between valve position and heat transferred. The simulation was carried out under the following conditions:

T11 = 65 °C
T21 = 5 °C

Secondary flow (m2) increasing from 10 to 100% Primary flow (m1) regulated to maintain T22 constant at 50°C. The size of the heat exchanger is the minimum possible in order to meet the sizing requirements. Constant differential pressure is maintained across the control valve. The load linearity is also affected by the authority of the control valve: low authority distorts the characteristics of the valve because its proportional pressure drop falls as its degree of opening increases. This does not, however, apply if the drop in presure across the valve is kept constant by means of a differential pressure control. In this case the authority of the valve.

As can be seen from fig. 5, the resultant valve characteristic curve is very close to linear, as would be expected on the basis of the relatively high temperature efficiency. Thus the conclusion must be that a water/water heat exchanger meeting modern sizing requirements, used with a linear control valve, will have almost linear relationship between valve travel and heat transferred. The general impression that significant non-linearities appear in this context is probably because of the fact that in other applications, e.g. air conditioning, sizing is often based on temperature efficiencies significantly lower than those in district heating systems where, starting from the desire for good cooling, such high temperature efficiencies are chosen that only the linear part of the heat exchanger characteristic is used.

2.2 Load linearity as against loop gain

All things being equal, it is desirable that loop gain be constant throughout the entire working range in all control systems. Constant loop gain requires that the relationship between a step applied at the control inlet and the resultant step in the controlled variable be constant throughout the entire working range. If this is the case, the same control amplification will be optimum across the entire working range, making allowances for the changes that can arise in dead times and rise times; see e.g. Hjorthol (1990). The fact that a heat exchanger circuit is load-linear by no means implies that loop gain is constant throughout the entire working range and that the system is thus optimal from the point of view of control technique, although this frequently seems to be the assumption. A load-linear exchanger circuit will have constant loop gain if there is a linear relationship between the load and the controlled variable. This would be the case if the load of the exchanger were controlled in accordance with a energy meter attached to the secondary side, an unusual thing in heating systems.

The parameter normally controlled is the flow temperature on the secondary side, and since there is a highly non-linear relationship between variations in heat load and variations in flow temperature (dependent on flow rate on the secondary side) a heat load-linear heat exchange circuit can show highly variable loop gain. This can be illustrated mathematically. Provided the characteristics of the control and actuator used are linear, the condition for constant loop gain can be expressed by:

$$\frac{ds}{dT_{22}} = C_1 \qquad (2)$$

where

s = valve travel
T22 = flow temperature on the secondary side (the controlled variable)
C 1 = a constant.

The relationship between variations in output and the flow temperature on the secondary side can be calculated as follows:

$$Q = m2 \cdot cp \cdot (T_{22} - T_{21}) \qquad (3)$$

$$dT_{22} = \frac{dQ}{m_2 \bullet cp} \qquad (4)$$

where

Q = output of the heat exchanger
cp = the specific heat capacity of the medium.

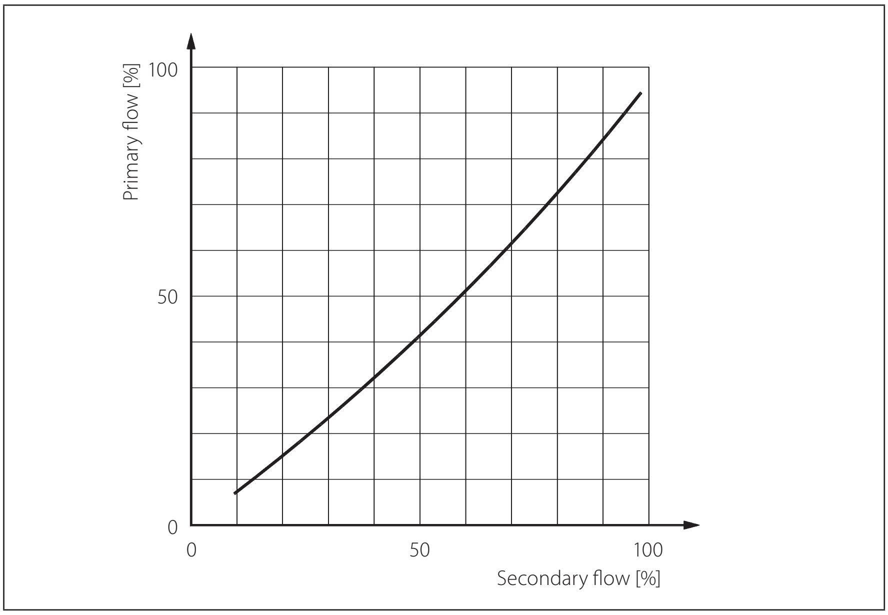


FIGURE 5: Relationship between primary and secondary flow in a heat exchanger with a relatively high temperature efficiency

Thus, by substitution in eqn. 2:

$$\frac{ds}{dQ} = \frac{C_1}{m_2 \bullet cp} \tag{5}$$

If as an approximation we regard the relationship between primary flow and the heat transferred as linear (see discussion in part 2.1) and regard cp as constant, the following will apply:

dQ » dm1 · C2 (6)

m2 » m1 · C3 (7)

where C2 and C3 are constants. Thus, by substituting eqns. 6 and 7 in eqn. 5:

$$m_1 \approx e^{\frac{1}{C_4} \bullet (s - C_5)} \tag{8}$$

where C4 = a constant.

If the differential equation in eqn. 8 is solved for s:

s » C4 · ln(m1) + C5 (9)

$$\frac{ds}{dm_1} \approx \frac{1}{m_1} \bullet C_4 \tag{10}$$

where C5 = a constant.

The result in eqn. 10 is very important. It demonstrates that constant loop gain in a heat exchange circuit with high temperature efficiency is achieved when the flow is altered by the exponent of the valve travel, and thus also by the exponent of the output signal of the control, if the actuator is linear.

As we know, this can be attained with the aid of an exponential valve characteristic. It will be noted that eqn. 10 is, basically, the equation for an exponential valve characteristic. This result is not unexpected. For example, Hjorthol (1990) arrived at a similar conclusion on the basis of a series of simulations of various load situations (Hjorthol (1990) page 77). In this instance, however, the result was attained by analytical considerations.

It must be emphasised that the use of an exponential valve is not actually necessary in order to achieve constant loop gain: it can equally well be achieved using a linear valve and then applying the exponential effect somewhere else in the control loop, e.g. in the actuator or the control. This solution has other great advantages in respect of operating time and regulating conditions, see below.

2.3 Practical consequences

The general assumption is thus quite reasonable, i.e. the best thing to use for controlling heat exchangers in district heating substations is normally a valve with exponential characteristics. However, the basis is not the nonlinearity of the heat exchanger but the non-linearity which is bound to arise in the control loop when primary side flow is regulated in accordance with the measurement of outlet temperature on the secondary side in order to keep the temperature constant (the traditional method of control).

Despite the fact that the result appears to be the same, it is very important to bear the correct principles in mind whenever working on the development and adjustment of control systems, otherwise seriously incorrect conclusions might be drawn.

On the basis of assumptions about non-linear heat exchangers several authors have concluded that valves with linear characteristics cannot be used to control exchangers. We shall now look at this conception on the basis of the relationships set out in part 2.1.

Firstly, it is impossible to draw any principle conclusions about optimum valve characteristics without taking the characteristics of all the other components of the control system into consideration at the same time. As we have seen, it is easy to achieve constant loop gain using a linear valve if exponential compensation is

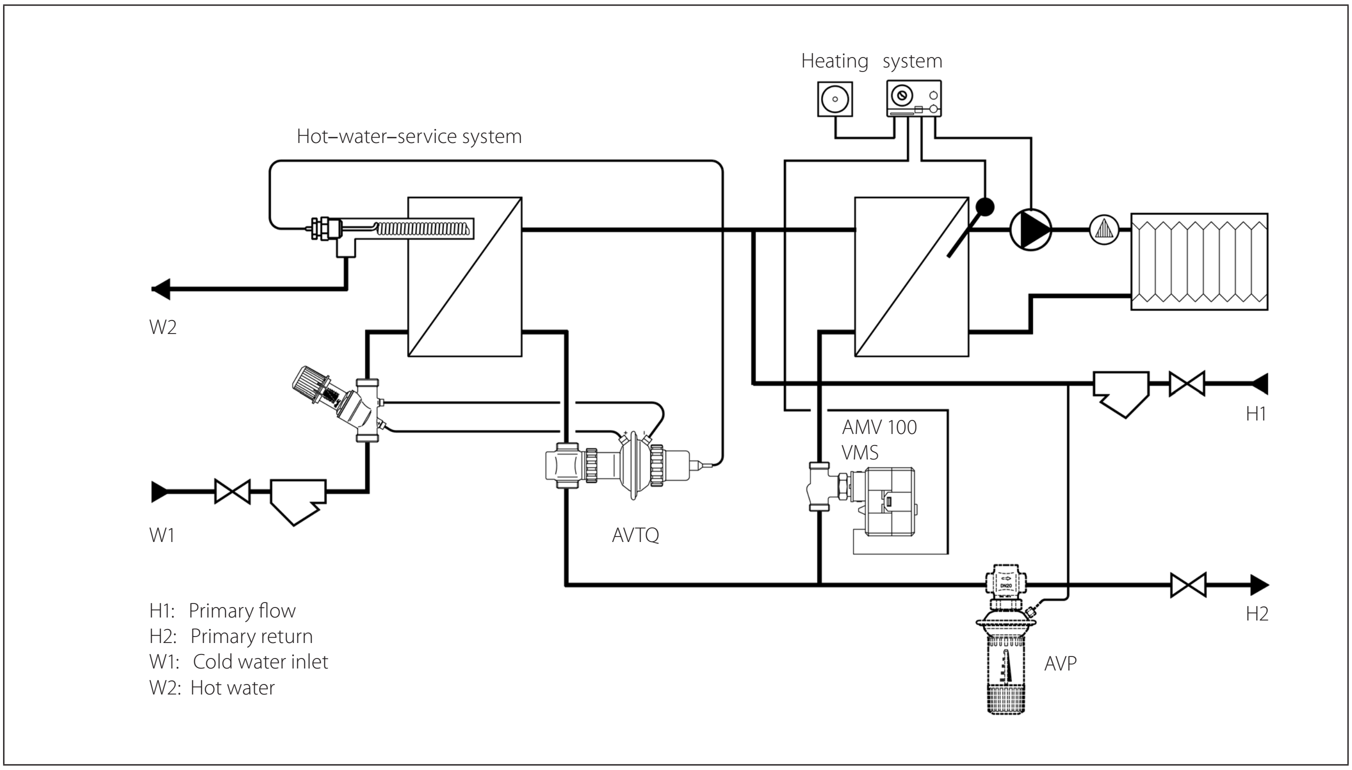


FIGURE 6: System diagram of a small district heating system with a selfacting temperature control type AVTQ in the hot-water service system

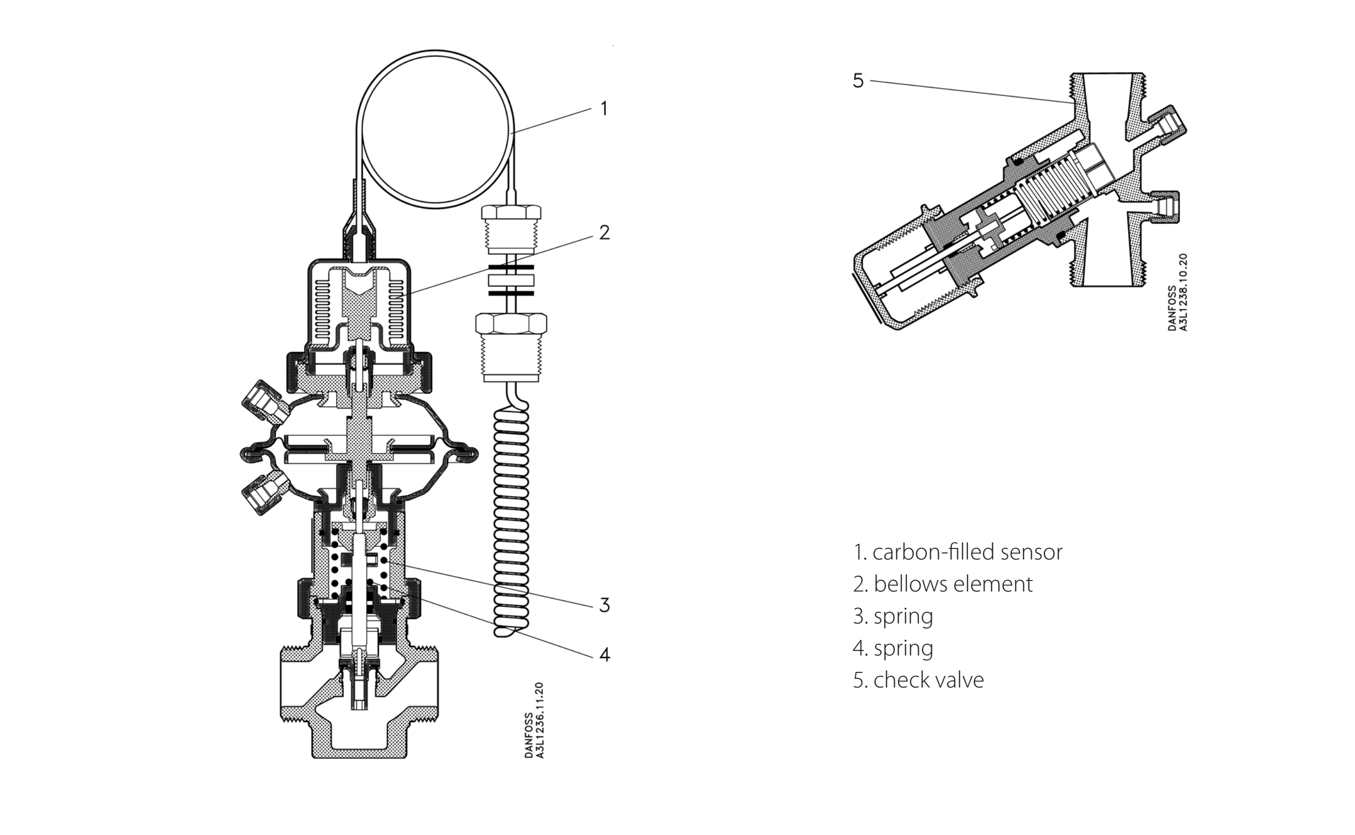


FIGURE 7: Self-acting temperature control type AVTQ

introduced somewhere else in the system e.g. at the control or the actuator. On this basis alone, it is impossible to draw any general conclusions regarding the characteristics of particular components. The system must be looked at as a whole.

However, let us assume the controls and actuators are linear, as most of them are.

Using a linear P-control, linear valve characteristics will require a relatively wide proportional band in order to obtain stability at low flow rates, resulting in comparatively high offset under high loads. On the other hand, exponential characteristics will give stable control at relatively low offset throughout the entire working range.

If however a PI control is used, the situation is somewhat different. Normally an exponential characteristic is still preferable, but excellent results can be achieved with linear valve characteristics, since the integral function will prevent permanent offset, even though a relatively wide P-band has to be used to give stable regulation at low flow rates.

Another advantage of linear valves is that in most cases they have a better control ratio than exponential ones. This is because it is very expensive to create the control ratio „natural“ to linear valves in exponential valves. And after all, adequate control ratio is the decisive factor in creating stable control under minimal load.

Valve travel is another aspect which needs taking into consideration in any discussion of the advantages and disadvantages of the characteristics of the various valves. In normal valves with linear travel, a valve with exponential characteristics typically has a travel four times that of a linear valve of the same capacity. All other things being equal, exponential valves therefore require a much faster - and thus much more expensive - actuator. Thus, although the control of heat exchangers by linear valve can be slightly sluggish because of their wide P-band, the final result can look rather different when the travel required is considered.

It is thus impossible to draw general conclusions about the various components of the control system, since the desired effect can be achieved in several ways.

What is most important is to understand the principle relationships discussed in parts 2.1 and 2.2, and on this basis take an overall view encompassing every single component of the control system.

3. The development of a self-acting temperature control for high-performance hot-water service heat exchangers

In Part 2 we considered some of the basic aspects of the control of heat exchangers from a theoretical point of view.

We shall now describe a practical method based on a newly designed self-acting control for small-scale instantaneous water heaters - the AVTQ.

The AVTQ is a self-acting temperature control designed to regulate the temperature of service hot water in instantaneous heat exchangers, see system diagram, fig. 6.

3.1 Dynamic simulation as a developmental tool

As the reader will see from the following description of the AVTQ, it is a highly advanced control seen from the point of view of control technology.

Since several different elements are included in the design (variable amplification, feed-forward etc.), with many possible combinations, it would be very time-consuming - as well as expensive - to find the optimum combination exclusively on the basis of laboratory experiments.

The development work was therefore a combination of theoretical analysis and laboratory experiments. The various possibilities were analysed with the aid of dynamic simulation, the most promising principles then being tested and adjusted in the laboratory.

This is where our simulation tool SIMULINK showed its worth. With the aid of simulation it proved posible to gain a high degree of insight into which avenues to explore and the way in which the various elements needed to be combined to give the best possible result.

The use of dynamic simulation thus contributed to a more goal-oriented course of development in which it proved possible at an early stage to see what was needed to achieve the desired result, and in which the actual design work was to a great extent a matter of converting theory into practice. The scope which dynamic simulation creates in connection with the development of components for district heating and central heating units is described in greater detail in Benonysson (1993).

3.2 Specifications

Right from the start, the highest standards were demanded of this control.

It had to be extremely fast in operation in order to prevent overheating and consequent lime deposition in the heat exchanger.

In the second place, stable control of the flow of service hot water was required in the 200 to 1200 l/h range, with a narrow P-band.

Thirdly, the control had to operate satisfactorily within a very wide spectrum of differential pressures and flow temperatures in the district heating system, the operating range of the first version being defined as differential pressure in the 0.2 to 4 bar range, and flow temperatures between 65°C and 100°C. In other words the control has to operate within a range where the one extreme is a secondary flow of 200 l/h at a differential pressure of 4 bar and a flow temperature of 100°C, and the other is a secondary flow of 1200 l/h at a differential pressure of 0.2 bar and a flow temperature of 65°C. Thus from a capacity point of view the operating range of the control is very wide, corresponding to a control ratio of about 1:60.

The first version was selected for district heating systems in which the above temperature and pressure specifications were sufficient. In the next version of AVTQ the maximum differential pressure will be increased to 6.0 bar and the maximum flow temperature to 130°C.

3.3 The control technology design

Since it is a complex and thus very expensive matter to attain an integraleffect in a self-acting control, the AVTQ is a „born“ P-control.

At the same time, for both technical and economic reasons, the control was given a valve with linear characteristics. An exponential valve with the necessary control characteristics would have cost much more, at the same time it would have been very difficult to provide the valve travel needed in an exponential self-acting control.

A linear valve in combination with a P-control with a wide P-band can be used in systems not demanding too much of the control, and in which the P-offset is acceptable.

However, as was explained in part 2.2, this combination of a P-control with a valve having linear characteristics is not very good at regulating heat exchangers which have to fulfil the previously mentioned requirements. In principle it does not matter where in the control loop the exponential effect is applied, and this fact is utilised in the new AVTQ as is also explained in part 2.2.

The control (fig. 7) is fitted with a carbon-filled sensor which has a large surface area and thus a short time constant (pos. 1). Pressure produced in the sensor varies linearly with the temperature of the sensor. The pressure is transmitted to the bellows (pos. 2), where it is converted to the force necessary to activate the valve. The amount of travel produced by any particular change in the temperature sensor is controlled by built-in springs (pos. 3 and 4), i.e. the spring constants determine the system loop gain.

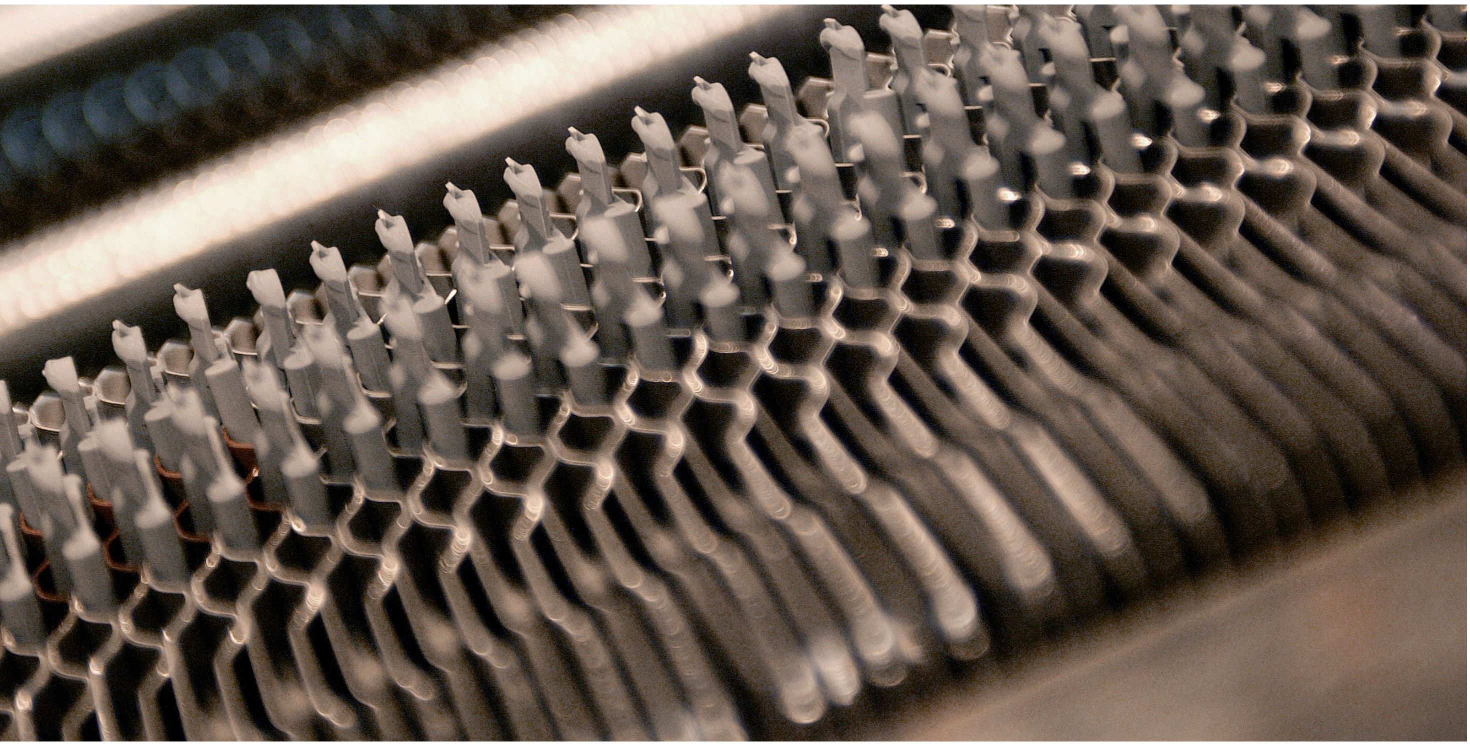
Introducing a spring with exponential characteristics gives loop gain linearisation, despite the use of a valve with linear characteristics.

In practice, however, it is impossible to use an exponential spring in this situation because of the comparatively short travel and the highly precise tolerances to which the spring would have to be made. Instead, an approximate exponential characteristic was obtained by using two springs, one of which comes into action just before the point of closure, reducing the amplification of the control under low load.

As can be seen from figs. 8a to 8b, this principle (which is now a patent) gives a split-range characteristic, despite the valve being very simple in design. The result of the break in the characteristic curve is that it is possible to operate with a much narrower P-band, giving less offset and stable regulation under low load.

To further reduce the effect of the P-band, as well as ensure a rapid reaction to changes in load, the control has a feed-forward function where set-point is directly affected by draw-off flow.

This is achieved by inserting a check valve with a special characteristics in the hot-water service circuit (see figs. 6 and 7, pos. 5) across which there is a pressure drop proportional to the draw-off flow, see fig. 9. The check valve is connected to a diaphragm element



in the control. This gives indirect flow metering in which variations in flow, and thus variations in pressure across the check valve, have a direct effect on the balance of forces in the control.

The set-point thus increases with increasing load and falls with decreasing load, markedly reducing the offset arising from the P-band. Note that the feed-forward function has no direct influence on loop gain and thus none on the stability of the system either. Complete equalisation of the P-band offset can, however, only be achieved by one particular combination of district heating flow temperature and differential pressure across the control valve. Any other combination will either lead to over-compensation or undercompensation.

As long as there is no flow on the secondary side (i.e. no load) the control operates at a no-load setpoint defined by the compression in the springs (factory set). The moment water is drawn off, the set-point is raised momentarily to the set value as a result of the opening pressure of the check valve (see fig. 9). When water ceases to be drawn off the set-point drops back down to the no-load temperature. The set-point on the control is determined by adjusting the opening pressure of the check valve.

This displacement of set-point, from operating temperature to no-load temperature when drawing-off stops, ensures that the control valve closes quickly, thus reducing excess temperature in the heat exchanger and thereby the risk of lime deposits. 4.

Conclusion

As we saw in Part 2, there is no one clear, true path to the regulation of heat exchangers. There are various methods, each with their own advantages and disadvantages, and in the final analysis it is functional demands and financial strictures which decide the right choice.

Part 3 describes the AVTQ control: an example of an alternative course. Despite the rather weak point of departure (a P-control and a linear valve), the application of various ideas and solutions has produced a control which fulfils many of the most important requirements for the regulation of service hot water. At the same time it is relatively inexpensive.

The conclusion thus is that regulating systems which are optimum both technically and economically are only possible if an overall view is taken on the basis of a real understanding of the physical relationships in which all elements of the control system are looked at as a unified whole.

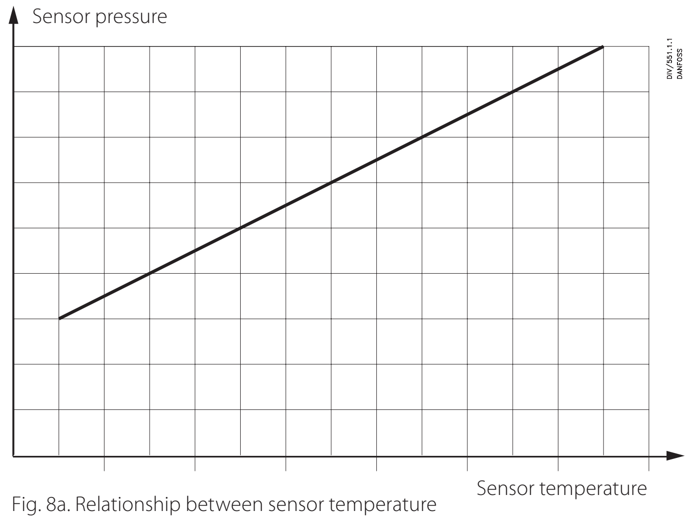


Fig. 8a. Relationship between sensor temperature and sensor pressure in a carbon-filled sensor

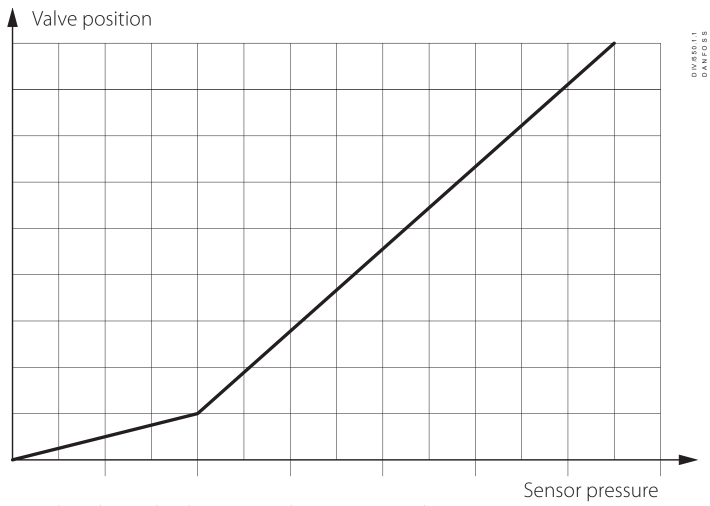


Fig. 8b. Relationship between valve position and sensor pressure in the split-characteristic of the AVTQ valve

FIGURE 8

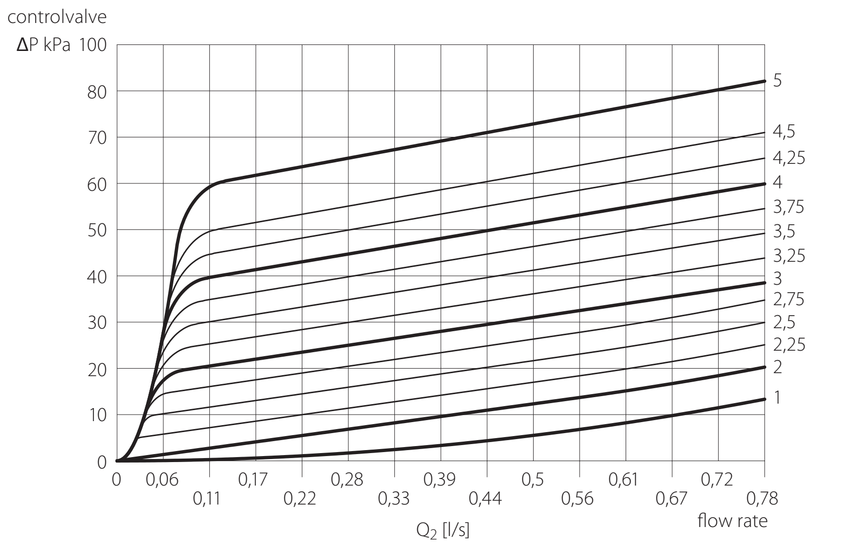


FIGURE 9: The check valve characteristic is proportional to the flow within the tapping range

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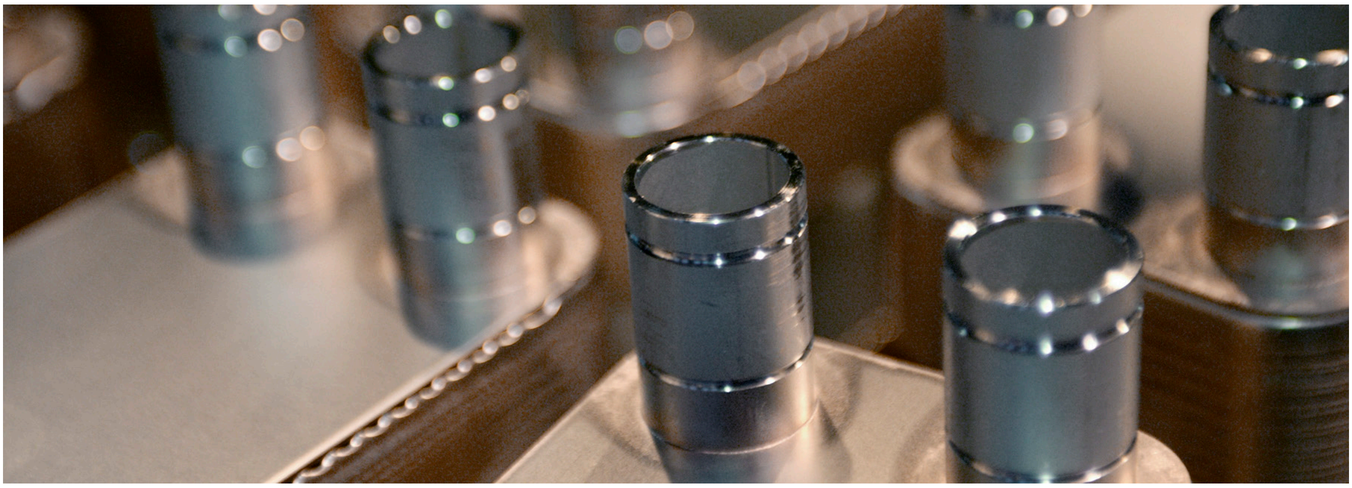

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