DESIGN OF HYDRAULIC CIRCUITS FOR CLIMATE INSTALLATIONS

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SUMMARY

The hydraulic circuit connects and influences the behaviour of all important components of a climate installation. A perceptive quantitative design of this part of a climate installation therefore seems natural and is necessary for installations with a heat pump or heat power connection. Actual practice shows that such is not the case and that especially control of part load operation of the hydraulic circuit should be improved. This article presents a method which at present is being worked out within The Netherlands by ISSO into a design guideline for advisers and installers.

1. INTRODUCTION

An important element during the realization of a climate control installation is the design of the hydraulic circuit. The hydraulic circuit is responsible for the distribution of the heat and cold capacities from the exciters to the consumers installed in various rooms of a building. The hydraulic circuit connects almost all components of a climate installation. This means that these components and the hydraulic circuits influence each other in such a way as that their individual characteristics are influenced. A soundly based design method for the hydraulic circuit therefore seems obvious.

Up to now the design of hydraulic circuits has been limited to full load situations. Based on the (calculated) capacities needed and chosen temperature levels for exciters and consumers, the full load volume flows are calculated. However, the full load situation is a situation that only occurs a couple of hours a year and does not have to lead to problems, provided the design volume flows have been balanced. If something goes wrong with the functioning of the hydraulic circuit and consequently the functioning of the climate installation this usually takes place during part load operation. As a result these are the situations which occur most frequently and which determine the indoor climate and energy consumption. Due to the rise of heating installations with heat pumps, heat power installations or remote heating, the necessity to better control the part load operation has become a topic. This article describes a method that takes both the full load and part load situation of a hydraulic circuit into account. The design method has a physical/mathematical basis and therefore a perceptive procedural character. At present ISSO is working on an ISSO-guideline for advisers and installers on the design of hydraulic circuits on which this article is based. In view of the magnitude of the subject this article is restricted to heating installations. The method for cooling installations runs analogous to that which is stated in the article about heating installations.

2. HYDRAULIC SUBCIRCUITS

The design of hydraulic circuits is complex, as a change in volume flow/pressure in one of the pipes due to a control valve also causes a change in the volume flows/pressures of the remaining pipes of this hydraulic circuit. The consequential physical/mathematical complexity is the reason that the present design methods hardly take part load operation into consideration. This complexity can be evaded by assuming hydraulic subcircuits during the design. Of these subcircuits the characteristics, i.e. volume flows and temperatures, during full load and part load can be specified, after which a complete hydraulic circuit can be composed from these subcircuits. The concept of subcircuits is explained by the hydraulic circuit for heating in figure 1. In this figure the arrows indicate where the various subcircuits for heat consumers and exciters begin and end. The shaded part represents the remaining distribution part.

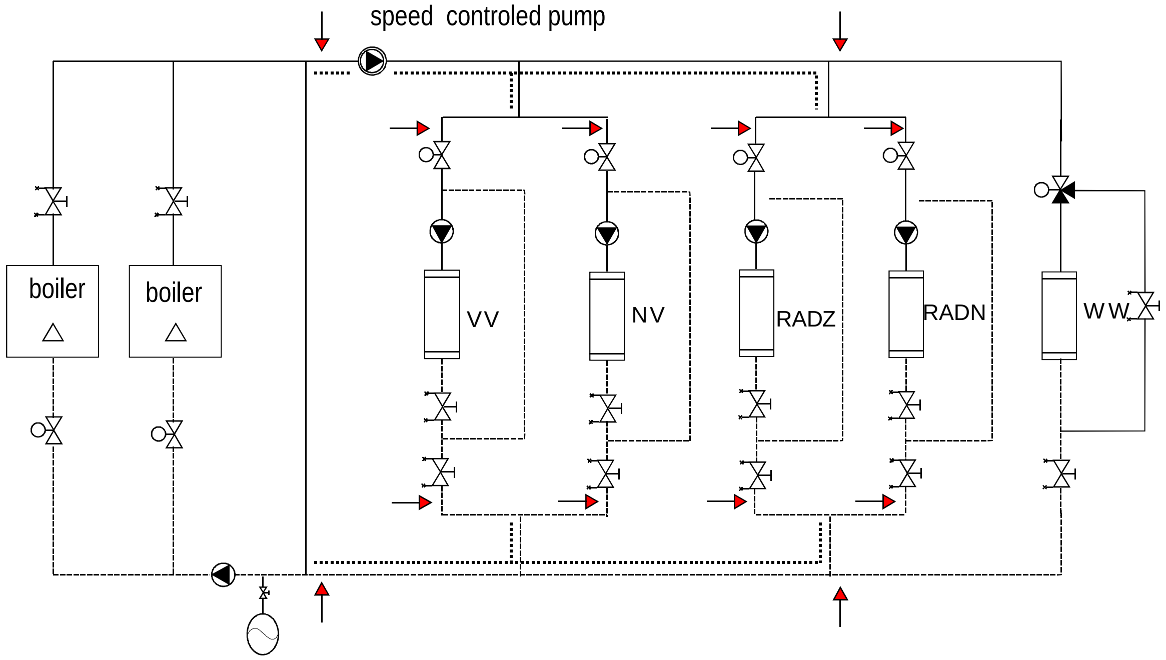


Figure 1.
Hydraulic circuit for heating and hot water. The different subcircuits have been indicated by arrows.

At the right of figure 1 the subcircuit for hot water (ww) is shown. The capacity of the boiler is controlled by dividing the flow with a three-way control valve. The 2nd and 3rd hydraulic subcircuit on the left are respectively radiator group north and radiator group south. The capacity of both radiator groups is centrally controlled by means of a mixing circuit with two-way control valves. For both radiator groups the rectangle represents a group of radiators (heat consumers), usually with decentral control by means of thermostatic control valves.

The 4th and 5th hydraulic subcircuit on the right are respectively an air reheater and an air preheater included in an air conditioning system. The air heaters are controlled by means of a mixing circuit. In this case the rectangular square represents a singular heat exchanger without decentral control. On the left of the figure there are 2 heat exciters with one pump, including open distributor/collector, this is the hydraulic subcircuit for the exciters.

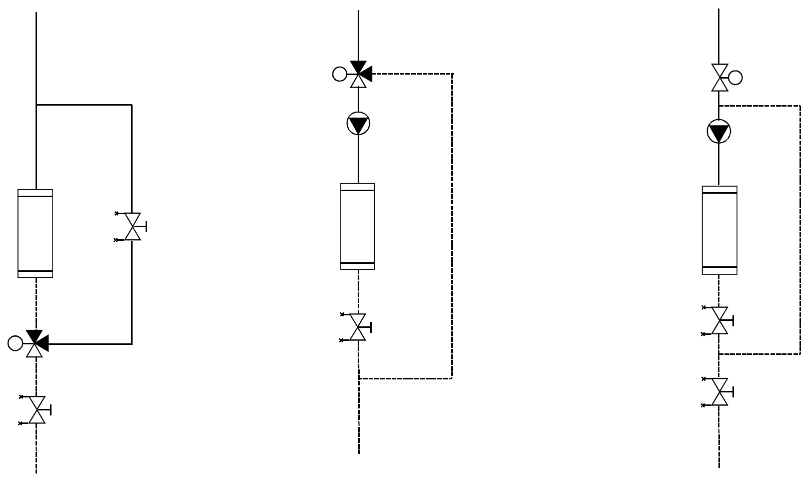
A definition for hydraulic subcircuit is the heat consumer(s) or heat exciter(s), including the hydraulic control for the benefit of the capacities of these heat consumer(s) or heat exciter(s).

The first step toward a design method is to standardize a number of hydraulic subcircuits.

2.1 Standardization of hydraulic subcircuits

In this chapter some standardized subcircuits are presented. They are subcircuits for heat consumers and subcircuits for heat exciters. The place and number of balancing valves in these subcircuits are determined on the basis of their function (balancing specific volume flow) and their influence on the part load operation of the subcircuit. This last aspect has been examined with the analysis of subcircuits to be discussed in chapter 2.2.

In figure 2 three standardized subcircuits for heat consumers are shown. Figure 2a concerns a dividing circuit in which the power used by the consumers is controlled by varying the volume flows. The figures 2b and 2c show mixing circuits where the power demanded by the consumer is controlled by varying the flow temperature. This is possible because the primary water is mixed with the return water of the consumer. The mixing ratio, that is the flow temperature to the consumer, is controlled in figure 2b with a three-way control valve and in figure 2c with a two-way control valve.



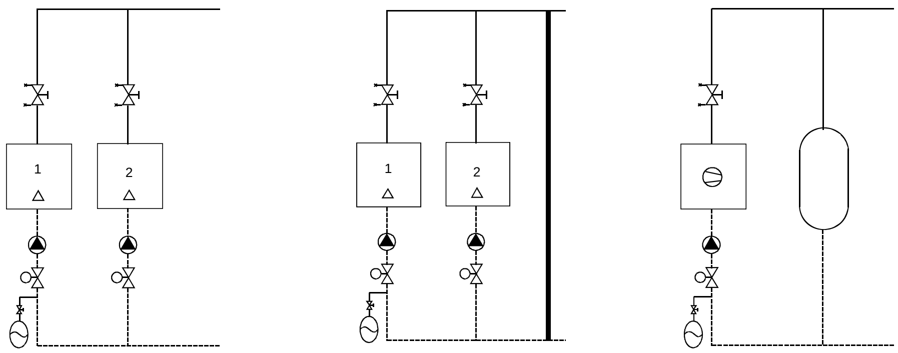
a) Dividing subcircuit with 3-way control valve

b) Mixing subcircuit with 3-way control valve

c) Mixing subcircuit with 2-way control valve

Figure 2.
Three examples of standardized subcircuits for heat consumers.

In figure 3 three examples are given for standardized hydraulic subcircuits for heat exciters. In figure 3a the subcircuit is composed of two parallelly connected boilers, each with its own boiler pump. Both boilers are connected to a closed distributor/collector. Figure 3b shows a similar configuration for heat exciters, but now both exciters are connected to an open distributor/collector. The open distributor/collector can be interpreted as a vessel to which the incoming and outgoing pipes of the heat exciter(s) and consumer(s) are connected. The hydraulic advantage of the open distributor/collector is that the flow regulation of the heat consumers hardly influences the volume flows in the boiler. Figure 3c shows a heat pump with a parallelly connected buffer vessel. This buffer vessel also serves as an open distributor/collector. In the subcircuits for heat exciters the balancing valves needed to adjust the design volume flows have been installed.



a) Two parallelly connected boilers with closed distributor/ collector

b) Two parallelly connected boilers with open distributor/ collector

c) Heat pump with buffer

Figure 3.
Three examples of standardized subcircuits for heat consumers.

The following number of subcircuits have been determined for the benefit of the design method to be developed:

- nine subcircuits for heat consumers, of which three have been discussed in this chapter;
- twelve subcircuits for heat exciters, of which three have been discussed in this chapter;
- nine subcircuits for cold consumers;
- four subcircuits for cold exciters.

2.2 Behaviour of hydraulic subcircuits

The selection of subcircuits during the design of hydraulic circuits takes place on the basis of the hydraulic and heat technical characteristics of these subcircuits. In short this means that the desired characteristics for full load and part load of the subcircuit are specified and that it has been indicated with which design rules the desired characteristics can be realized. To understand the behaviour of a hydraulic subcircuit use has to be made of physical/mathematical models. There are two situations that may occur.
The first situation is that the desired characteristics are sufficiently known but that the design rules to achieve the desired situation are missing. The second situation implies that so little is known about the behaviour of a subcircuit that it is not possible to specify the desired characteristics beforehand. In this case the behaviour of the subcircuit should be studied by means of the analysis of the mathematical model, so that requirements for the desired behaviour may be derived, as well as the design rules to achieve this behaviour. In this article we assume the easy situation where it is possible to specify the desired characteristics beforehand

The specification of the desired hydraulic and heat technical characteristics for full load and part load situations is worked out for the mixing circuit with a three-way control valve (figure 2b). In figure 4 this subcircuit for heat consumers is shown again, this time including the various volume flows and temperatures.

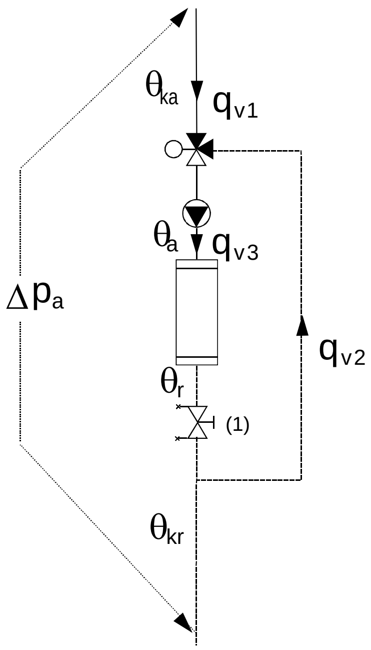


Figure 4.
Subcircuit for heat consumer(s), being a mixing circuit with a three-way control valve, including the volume flows and temperatures.

Assuming the volume flows and temperatures defined in figure 4, the desired behaviour of the mixing circuit during full load and part load situations has been specified in table 1.

Table 1.
Requirements for the desired behaviour of the mixing circuit with a three-way control valve. In this table the decentral control of the heat exchangers and heating curve regulation for θ_{ka} have been ignored.

Situations	Volume flows	Temperatures	Other
Full load (100 %) realization with balancing valve 1	– $q_{v3,100}$ = design volume flow*) – $q_{v1,100} = q_{v3,100}$ – $q_{v2,100} = 0$	– $\theta_{a,100}$ = design principle*) – $\theta_{r,100}$ = design principle *) – $\theta_{ka,100} = \theta_{a,100}$	-
No load (0 %)	– $q_{v3,0} \approx q_{v3,100}$ – $q_{v1,0} = 0$ – $q_{v2,0} = q_{v3,0}$	– $\theta_{ka,0} = \theta_{ka,100}$ – $\theta_{a,0} = \theta_{r,0}$	-
Part load	$q_{v3,100} \leq q_{v3} \leq 1{,}1 \cdot q_{v3,100}$	– $\theta_r < \theta_a \leq \theta_{ka,100}$ This requirement means that the volume flow q_{v2} is not allowed to change direction during part load.	Requirement for linearity between the regulated quantity and the control valve

*) results from a design calculation or design principle.

The behaviour for full load as specified in table 1 is realized by balancing valve 1. The other desired characteristics, in particular those for part load, are achieved by the choice of the type of control valve, authority of the control valve and hydraulic resistance of the pipes.

Appendix 1 gives some results of the physical/mathematical model for the mixing circuit with a three-way control valve. The modelling results in a number of dimensionless characteristic numbers for the relevant subcircuit, which determine the behaviour. Through analysis the values of the characteristic numbers are determined which results in the desired behaviour of the subcircuit. The dimensionless characteristic numbers, being authority, resistance ratio of pipes of the subcircuit and the connecting pressure should be translated into concrete design rules which will help the designer to do his job.

An example of this is given in table 2. The desired behaviour of the subcircuit for heat consumers is graphically represented and the design rules to reach this desired behaviour are specified at the bottom left. The designer should not be bothered with the physical/mathematical analysis as discussed in appendix 1.

The influence of the alien (from another pump) connecting pressure Δp_a on the behaviour of the subcircuits is used for the composition of the various subcircuits. In its most simple form this could mean that the connecting pressure Δp_a for the subcircuit is to remain constant during part load situations.

Table 2

3. COMPOSING THE HYDRAULIC CIRCUIT

3.1 Requirements for the hydraulic circuit and its components

The choice of the hydraulic subcircuit for heat consumers and heat exciters is based on the requirements which amongst others the heat exciters and heat consumers have to meet. With respect to the heat exciters it is often required that the volume flow is kept constant or that a minimal value is not underspent. A high efficiency boiler only reaches its high efficiency if the return temperature is sufficiently low. For heat pumps it is required that the volume flow is constant and the return temperature to the condensor sufficiently low. Similar requirements have to be met for heat consumers. To prevent freezing of a preheater, the volume flow should be constant and the temperature sufficiently high. For radiators it will be necessary that a minimal volume flow is not underspent in order to ensure that the radiator/convector remains effective over the entire length.

On the basis of these requirements the designer selects the appropriate subcircuits for heat consumers and heat exciters. To this effect he uses the hydraulic and heat technical characteristics which are given per subcircuit on one A4, such as in table 2.

That what remains is the composition of the selected subcircuits to one complete hydraulic circuit. Basic principle is that the selected (desired) characteristics for the subcircuits are not lost. This is achieved by using the design rules during the composition which are explained in the following chapters.

3.2 Design rules for composition

The results of the analysis in appendix 1 show amongst others that the inclusion of a pump in the supply pipes of the subcircuits with a three-way control valve has a negative effect on the functioning of the subcircuit. The volume flow q_{v2} has changed its direction over a wide range of the control valve, as a result of which there is no mixing but dividing at the three-way control valve. The reason is that the pump included in the subcircuit is also capable of generating volume flows in the pipes outside this subcircuit and that a second pump is not needed. We therefore call this subcircuit active. There are also subcircuits which are not capable of generating volume flows in pipes outside the subcircuits. These circuits we call passive. The passivity of the subcircuits is usually caused by an open distributor/collector or short circuit pipe, over which the pressure difference is no more than approximately 1 kPa.

Based on the above definitions for active and passive this character can be added to the subcircuit discussed in this article.

<u>Subcircuits for heat consumers</u>

– figure 2a dividing circuit (no pump)	passive
– figure 2b mixing circuit with three-way control valve	active
– figure 2c mixing circuit with two-way control valve	passive

Subcircuits for heat exciters

- figure 3a two parallelly connected boilers with closed distributor/collector — active
- figure 3b two parallelly connected boilers with open distributor/collector — passive
- figure 3c heat pump with parallelly connected heat buffer — passive

If we add active (with pump) or passive (without pump) distribution pipes to the subcircuit for heat consumers and heat exciters the first design rule for composition of subcircuits is as follows.

A	Subcircuit for heat exciters **Passive**	combine with	Distribution **Passive**	combine with	Subcircuit for heat consumers **Active**
B	Subcircuit for heat exciters **Passive**	combine with	Distribution **Active**	combine with	Subcircuit for heat consumers **Passive**
C	Subcircuit for heat exciters **Active**	combine with	Distribution **Passive**	combine with	Subcircuit for heat consumers **Passive**

The first design rule for composition prevents that consequently too many pumps with the undesired behaviour during part load are included in the hydraulic circuit. However, this does not guarantee that the connection pressure Δp_a over the subcircuits is sufficiently low or constant. These conditions for the connection pressure follow from the analysis of the subcircuits and are realized by:

- constant volume flows in the distribution pipes;
- pressure difference regulators;
- speed regulated pumps.

In the figures 5 en 6 two hydraulic circuits are shown which are composed of the subcircuits discussed in this article, for which use has been made of the first design rule for composing.

Figure 5 shows a small hot water heating installation for a single-family dwelling.

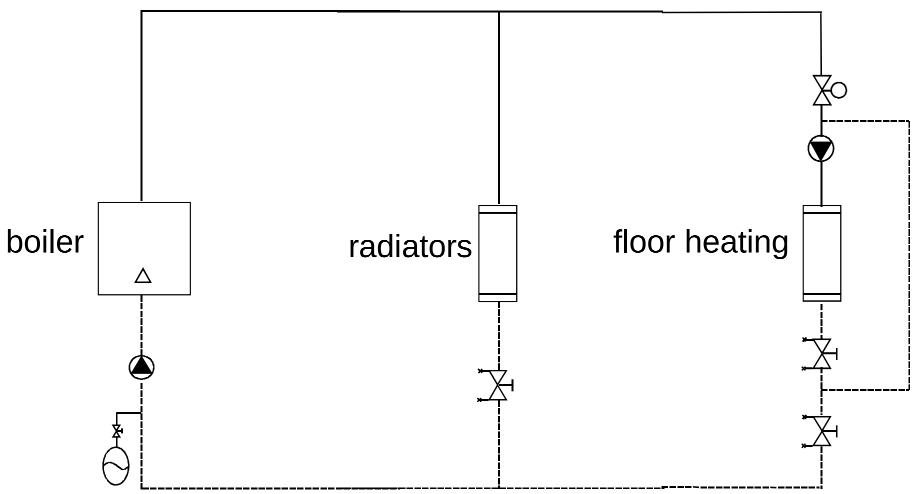


Figure 5.
Heating installation for a single-family dwelling consisting of floor heating and radiator heating.

The subcircuit for the boiler (active) is connected with the subcircuit for radiators (passive) and the subcircuit for floor heating (passive). The design rule for composition is applied for each subcircuit that is added to the hydraulic circuit. The boiler is highly fired so that by means of premixing the temperature of the floor heating should be lowered to approximately 50 °C. The possibility of premixing is a hydraulic characteristic of the relevant subcircuit, which has been chosen for floor heating, and is realized with the balancing valves.

Figure 6 shows a bigger hydraulic circuit for e.g. an office-building. The heat consumers from right to left are respectively:

- boiler for hot water connected to a dividing subcircuit with a 3-way control valve;
- radiator group north, connected to a mixing subcircuit with a 2-way control valve;
- radiator group south, connected to a mixing subcircuit with a 2-way control valve;
- air heater north, connected to a mixing subcircuit with a 2-way control valve;
- air heater south, connected to a mixing subcircuit with a 2-way control valve;

In this case no premixing in the full load situation of primary flow and return flow is allowed for the heat consumers, which can only be realized with the balancing valves.

The heat consumers are connected to two parallelly connected exciters which are linked to an open distributor/collector.

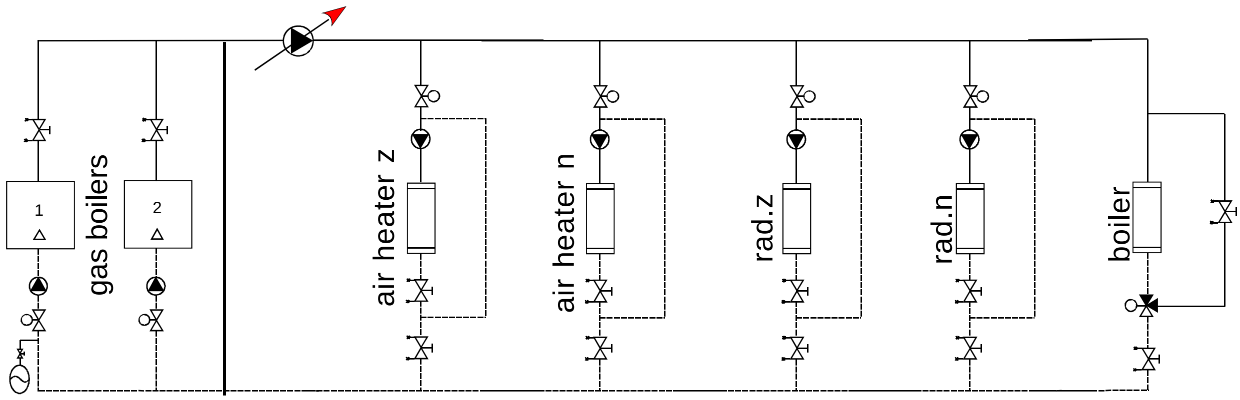


Figure 6.
Hot water heating installation for an office. The heat consumers from right to left are respectively boiler, radiators north, radiators south, air heater north and air heater south. The consumers are connected to two parallelly connected boilers with open distributor/collector.

Both the subcircuits for heat consumers and the subcircuits for exciters have the characteristic passive. As regards the active distribution composition rule B is applied.

In the first instance the speed regulated pump takes care that the pressure difference over the subcircuitry for heat consumers remains as constant as possible, which is necessary for a good functioning, which follows from analysis. Secondly the energy consumption of transport is reduced by means of the speed regulated pump.

3.3 Dimensioning of pipes and pumps

By making use of subcircuits and design rules for composing, the designer is already far with the realization of a hydraulic circuit, which functions according to the specifications. It can only still go wrong if the pump has not been dimensioned correctly and as a result has too little head. This part is considered elementary for each designer and will not be further explained in this article.

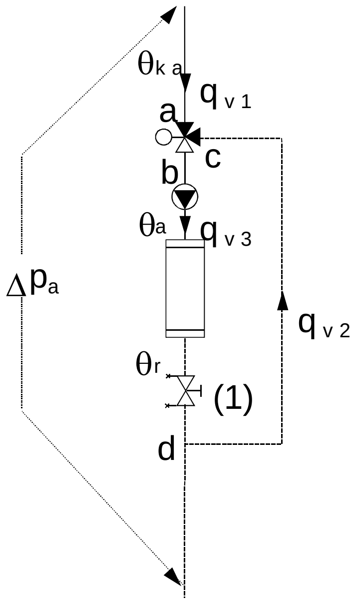
4. CONCLUSIONS

The present design methods for hydraulic circuits do not meet today's requirements. Particularly part load, which is decisive for the indoor climate and energy consumption, is insufficiently mastered. This issue emphatically came up during the introduction of heating systems with a heat pump or heat power as exciter. Many of these installations fell short of expectations and research showed that insufficient attention had been paid to the behaviour of the hydraulic circuit during part load operation.

With the design method for hydraulic circuits, as explained in this article, it will be possible to take full load and part load situations into account during the design. The design method is based on a standardized number of hydraulic subcircuits for heat consumers/cold consumers and heat exciters/cold exciters. Of the subcircuits the characteristics with respect to volume flows and temperatures for full load and part load are known. Complete hydraulic circuits, which meet the requirements specified beforehand during full load and part load situations, are composed by means of the subcircuits making use of a few simple design rules for composing. The design method is easy to use for advisers and installers, which is surprising considering the mathematical complexity of the description of part load operation of hydraulic circuits. In The Netherlands this method is worked out by ISSO into a standardized design guideline for adviser and installer. It is recommendable that the method also obtains a firm footing in other countries.

APPENDIX 1: ANALYSIS OF THE BEHAVIOUR OF THE HYDRAULIC SUBCIRCUITS

The modelling for each subcircuit consists of the formulation of equations, based on conservation laws for volume flows and pressure. This is carried out for a random part load situation and the full load situation. Subsequently the equations are rendered dimensionless and solved with the aid of the numeric method Newton-Rapson. For the heat consumption subcircuit, being a mixing circuit with a three-way control valve, this modelling results in 5 dimensionless characteristic numbers which determine the hydraulic behaviour of the subcircuit. The heat technical characteristics can be added to the model by means of two extra dimensionless characteristic numbers, but are ignored in this appendix.



Dimensionless characteristic numbers for full load which determine the hydraulic behaviour of the subcircuit during part load

- $A = \dfrac{\Delta p_{vab,100}}{\Delta p_{vab,100} + \Delta p_{ad,100}}$ (authority)
- $B = \dfrac{\Delta p_{cd,100}}{\Delta p_{ad,100}}$ (pressure ratio pipes)
- $C = \dfrac{\Delta p_{bd,100}}{\Delta p_{ad,100}}$ (pressure ratio pipes)
- $X = \dfrac{\Delta p_{a}}{\Delta p_{ad,100}}$ (pressure ratio connection pressure and pipe ad)
- $Y = \dfrac{\Delta p_{p}}{\Delta p_{ad,100}}$ (pressure ratio maximal head of pump and pipe ad)

100 = full load

Figure 1a.
Subcircuit for heat consumer, being mixing circuit with three-way control valve. In case of decentral control, the pressure loss Δp_{bd} and thus the pressure ratio C is variable.

In the following text a number of results of the analysis are graphically represented. The figures 1b and 1c show the desired hydraulic behaviour for a linear control valve and an equiprocentual control valve.

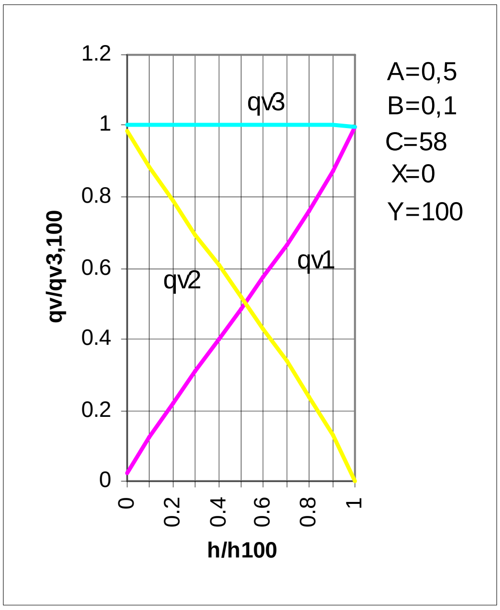


Figure 1b.
Desired hydraulic behaviour if during design a linear complementary three-way control valve has been chosen

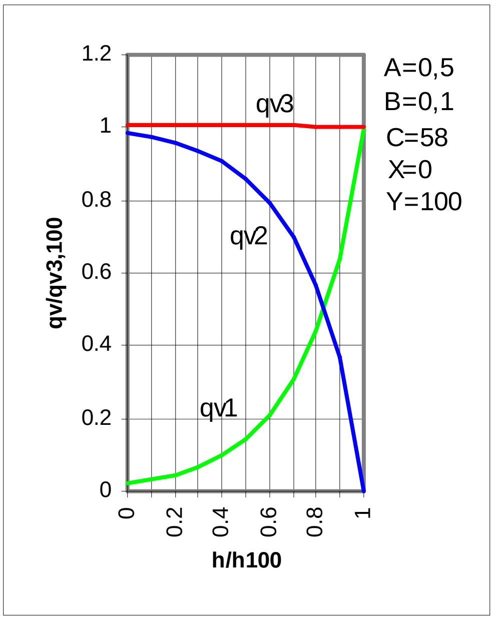


Figure 1c.
Desired hydraulic behaviour if during design an equiprocentual complementary three-way control valve has been chosen

In the figures 1b and 1c there is no decentral control by means of thermostatic two-way control valves.

Figure 1d shows the influence on the hydraulic behaviour if the return pipe dc has a high resistance, e.g. as an result of the installation of a balancing valve. Here a linear three-way control valve is assumed. It is clear that a too high resistance in the pipe dc does not influence the desired behaviour (see figure 1b) and therefore an extra balancing valve will not be necessary.

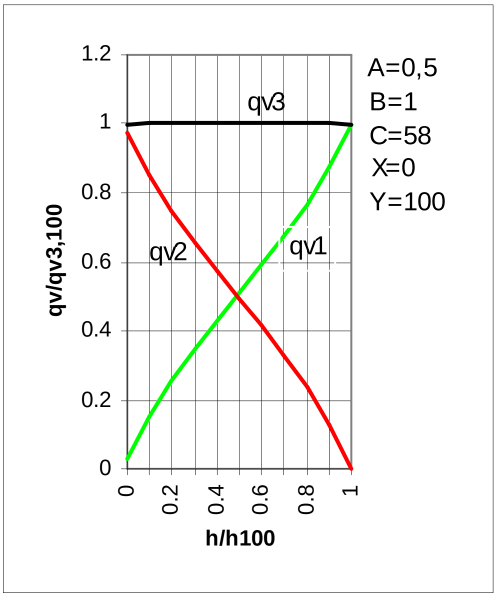


Figure 1d.
Hydraulic behaviour if the resistance in the return pipe dc is too high.

Figures 1e and 1f show the influence of a low authority A = 0,2 on the hydraulic behaviour. Here a linear three-way control valve is assumed. The value of the authority is determined during the design. For this subcircuit it shows that if the resistance bd is low (one heat exchanger, figure 1e) the influence of the authority is great and if the resistance bd is high (many heat exchangers, figure 1f), the influence of the authority is small.

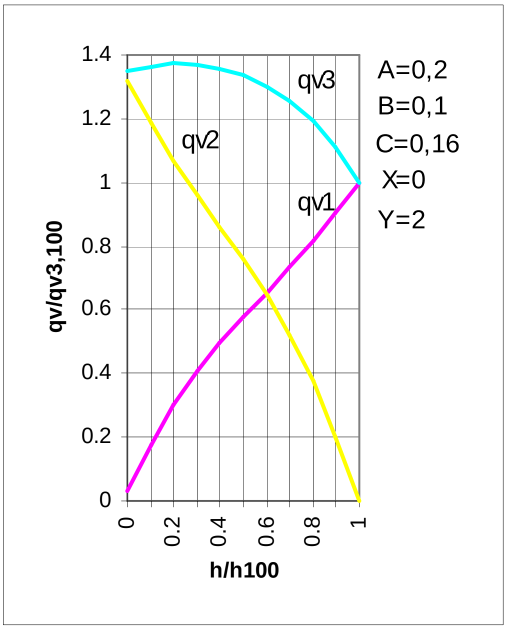


Figure 1e.
Influence of a low authority A = 0,2 on the hydraulic behaviour if the resistance bd is low (one heat exchanger)

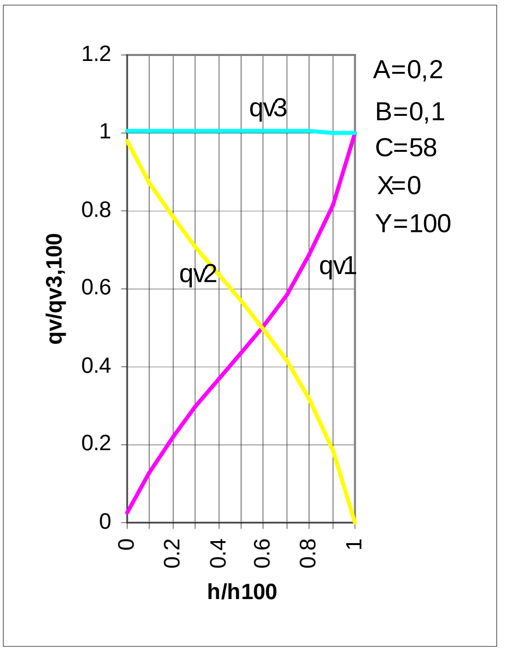


Figure 1f.
Influence of a low authority A = 0,2 on the hydraulic behaviour if the resistance bd is high (many heat exchangers)

Figure 1g assumes decentral control of the heat exchangers with thermostatically controlled two-way control valves. This results in an increase of the resistance bd during part load. Besides, the subcircuit is connected to e.g. a boiler with a boiler pump, which translates itself into a positive connection pressure Δp_a .

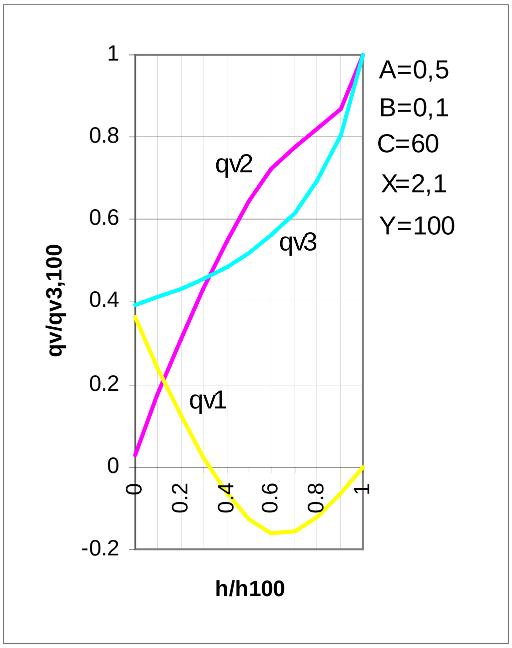


Figure 1g.
Undesired hydraulic behaviour at decentral control of the heat exchangers and positive connection pressure Δp_a .

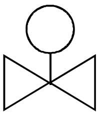
The volume flow in the return pipe cd changes direction for a large part of the control range of the control valve, so that there is no question of a mixing valve but of a dividing valve. The regulation is forced to put the control valve to the almost closed position in order to make mixing possible. This is accompanied by commuter behaviour of the control valve and an increased energy consumption for transport . Decentral control at this subcircuit is possible but then the connection pressure Δp_a should almost be nil. This can be realized by employing the rules for the composition of subcircuits discussed in this article.

The conclusion of this appendix is that by means of a physical/mathematical analysis of the subcircuits design rules can be laid down, which determine the behaviour of the hydraulic circuits during full load and part load situations. These data should be worked out in such a way that a simple practically applicable design method, such as discussed by this article and shown in table 2, results.

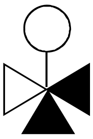
SYMBOLS

q_v	volume flow	[m^3/s]
θ	temperature	[°C]
h	position of control valve	[m]
h/h_{100}	relative position of the control valve	[-]
Δp_a	connection pressure subcircuit generated from alien source	[Pa]
Φ	heat capacity	[W]
Δp_v	pressure difference valve	[Pa]
Δp	pressure difference pipe	[Pa]
Δp_p	maximum pressure (head) of a pump	[Pa]
A	authority	[-]
B	pressure ratio pipes	[-]
C	pressure ratio pipes	[-]
X	pressure ratio connecting pressure and pipe ad	[-]
Y	pressure ratio maximal head of pump and pipe ad	[-]
100	index for full load or fully opened control valve	

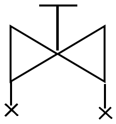
GRAPHICAL SYMBOLS



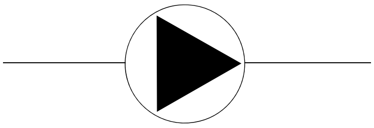
two-way control valve with servo motor



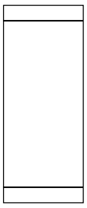
three-way control valve with servo motor



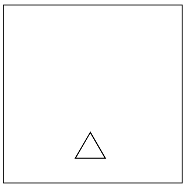
balancing valve with measuring nipples



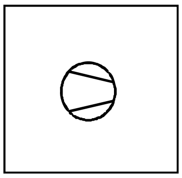
pump



heat exchanger or group of heat exchangers with or without decentral control



heat exciter, being a boiler



heat exciter, being a heat pump

LITERATURE

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