Design principles for hydronic heating systems
Constant and variable flow control systems

Master of Science Thesis in the Master's Programme Structural engineering and building performance design

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ABSTRACT

The conventional way of regulating the heat to a heater has for a long time been to use shunt groups and a constant water flow. In later times, a new way of constructing heating circuits is to regulate the heat output by vary the water flow to the heater. The purpose of this report is to study these two ways of regulating the heat output. The advantages and disadvantages of both the constant flow system and the variable flow system are studied and analyzed in this report. The possibilities and limitations of using these two systems are also studied. Especially, pumps and their function have been studied in order to see whether it is possible to effectively use them in a flow control system or not. An experimental study about two types of pumps is also described and the result of it is written and analyzed in this report. The purpose of the experimental study is about two different pumps that have been tested mainly with regard to energy use. The results of the report show that a flow control system has a big potential to save energy on driving the pump. A variable flow system on needs to run at ineffective speeds a lot of time but the laboratory shows that there is still a big potential to save energy on the pump if a variable flow system is used instead of a constant flow system. In the report it is possible to see different ways a pump can be controlled. The latest pump generations is well adopted to be used in a variable flow system. This is for instance because that in a variable flow system, the pressure loss in the pipes changes depending on the magnitude of the flow. A controlled pump can automatically change its speed and create the "right" pressure increase for when the flow changes. The usefulness of using variable flow system is also discussed in the report. Since an increased energy use in a pump, is turned into heat that will heat up the water that in turn, is used in the heaters. This is, however, not an effective way of heating water.

Key words: Hydronic heating systems, Flow control, Constant flow, Pump, Energy
use

Design principer för vattenburna värmesystem
Konstant och variabelt flödesreglerings system
Examensarbete inom Structural engineering and building performance design

Institutionen för Energi och Miljö
Avdelningen installationsteknik
Chalmers tekniska högskola

Sammanfattning

Denna rapport handlar om vattenburna värmesystem. Den handlar om konstantflödessystem såväl som variabla flödessystem. Pumpar är i fokus i rapporten. Den tar upp hur pumpar kan regleras och hur energi åtgången ser ut för olika pumpar. Den beskriver också hur värmekretsar kan se ut för både konstantflödessystem såväl som för variable flödessystem.

Nyckelord: Vattenburna värmesystem, Konstant flödes system, Variabelt flödes system, Pumpar, Energi användning

Contents

Preface

This report is a master thesis at Chalmers University of technology in the master program Structural engineering and building performance design. I would like to thank my supervisors at Chalmers; Jan Gusten, Torbjörn Lindholm, and Mattias Gruber for their help during this project work. I would also like to thank Rolf Jonasson at Wilo for his help during my project work.

Göteborg November 2010

Martin Olsson

Notations

Figure	Designation
	Heater
	Balancing valve
	Shut off valve
	Control valve
	Check valve
	Pump /Controlled pump
	Temperature sensor

1 Introduction

1.1 Background

The conventional way of designing heating systems is to use shunt groups. In this way the heating power is regulated by temperature. This is done by letting some of the water from the heater outlet mix with the "new" water, in order to get the temperature that is needed to get the right heating power. In this system the flow is then kept constant and the different components in the heating system can be dimensioned for that flow.

The problem with this system is that the pump needs to work at a high speed all the time and pump a lot of water even though the heating demand is very small. This system also requires extra equipment to operate. Before each heater or radiator, there needs to be one extra pump and one pipe with valves connecting between the supply- and exhaust pipe.

A new way is to remove the shunt group and instead regulate the heat power to the heaters and radiators by changing the amount of water going the heaters or radiators. In this way, there is possible to remove the extra pump and other equipments. It has also the potential of saving pump drive power energy.

1.2 Purpose

The purpose of this report is to study flow control and to compare it to constant flow systems. It is the purpose to examine how flow control works and how it can be realized. This report looks at the different components and sees how they can be used to make it possible to use flow control. Especially, what are studied are pumps and their function and different ways to operate and how they can be used in flow control. Furthermore, is the energy usage analyzed in order to examine how much the gain can be if flow control is used instead of a constant flow system.

1.3 Method

A literary study was made in order to find the basic information on how heating circuits and the different components work. Additional literature was then studied in order to find the basic knowledge on what constant flow system and flow control systems are and why they are being used and when. After that a number of pumps of a certain brand of pumps were studied to see how they can help to create and to maximize the efficiency of a flow control system. A real system was also studied in order to see how both a constant flow system and a flow control system can look like. This was done by looking at a real heating circuit and then to see how it would look like if it were changed from a constant flow system into a flow control system and vice versa.

At the end, an experimental study was made where pumps were studied. In that laboratory work, an ordinary constant speed pump was compared to a speed controlled pump. Especially, the drive power of the pumps was studied.

2   Heating circuits to the heater

In design of heating system one can use either a system with constant flow and to regulate the heating power by temperature regulation or it can be done by using a variable flow system. This chapter gives the basic knowledge for those systems and to look at general theory of water based heating systems. It also explains what a constant flow system and flow control systems are and their advantages.

2.1   Theory

There are mainly two different types of distribution system; 2-pipe distribution system and 3-pipe distribution system. The 2- pipe distribution system is the most commonly used in Sweden. The radiators are connected parallel to each other. See Figure 1. In this system, the differential pressure will vary a lot between the different components due to the pressure loss inside the pipes. The pump capacity needs to be adjusted to fit the pressure loss for the last component. The other components will then be fitted with valves in order to compensate for the different pressure losses. [11]
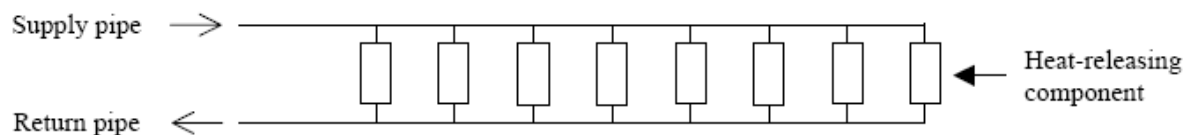
***Figure 1**. 2-pipe distribution system.* [11]

A 3- pipe distribution system is a system where the pipes for the return water are connected inversely. The components that are first in line on the supply line are then the last in line on the return pipe. See Figure 2. This means that the pipes are all the same length and because of that also the pressure loss. In reality it is however hard to achieve a perfectly balanced system. Valves are therefore necessary to create a balanced system. A problem with this system is that it is not very flexible to changes, since changes can result in unbalanced pressure loss. [11]
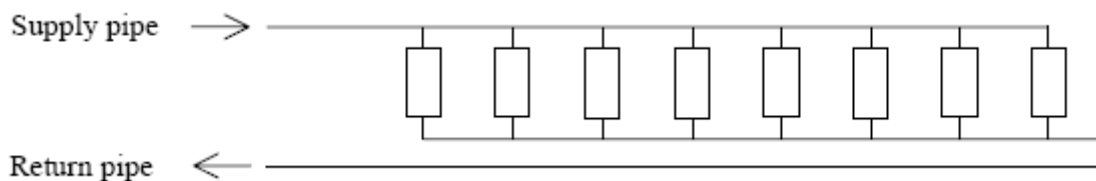
***Figure 2**. 3-pipe distribution system.* [11]

There are different categories of hydronic heating systems; there are low temperature systems and high temperature systems and there is low flow as well as high flow systems. More of this will be given in a later Chapter. [11]

2.2 Constant flow

In a system with a constant flow, the temperature needs to be regulated in order to get the right heating power to a heater or a radiator. Since the flow is constant the pumps will always work at a constant speed. Therefore it can work at its most optimal speed. It will however be designed for maximum flow. This will require a high work from the pump and will demand a lot of energy. In order to get a right heating power, the temperature needs to be changed with a constant flow. This must be done by bypass channels. [4]

In order to get different temperatures to the heaters without changing the flow shunt groups are often used. They mix the supply water with the return water from the heaters in order to get the right temperature. By doing this the water flow will be constant. There are many different variants of shunt groups. [4]

One way is to use a two way valve which creates a constant flow on the secondary side and a variable flow on the primary side. See Figure 3. The advantage of this system is that it will generate a high temperature drop and thereby more efficiency using the energy in the heat. It is often used in district heating systems. [9]
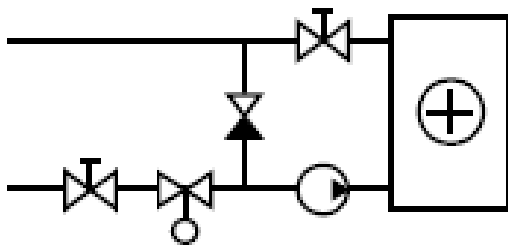
Figure 3. *Shunt group with constant flow on the secondary side and a variable flow on the primary side.* [11]

Another way is to use a constant flow over the primary side. It will only generate a small temperature difference and is therefore mainly used in a system with an own energy source. This is often called a Swedish connection. [9] See Figure 4
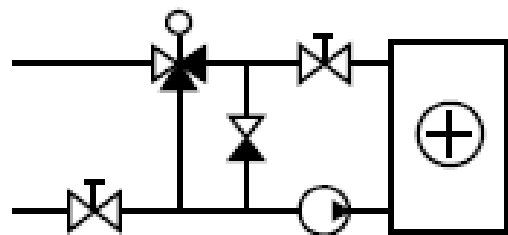
Figure 4. *Shunt group with constant flow on the primary side.* [11]

2.3   Flow control

An alternative system is to use a variable flow system. An advantage with this system is that its friction losses become smaller than in a constant flow system. This is because the flow often does not need to be as large as the system is dimensioned for. This results in that the pump does not need to work at its maximum all the time and thereby saving a lot of energy. Since the energy given off to the heaters is dependent on the flow, the temperature difference can be maximized. [4]

See Figure 5. When choosing type of system, it is important to use a system with high air heater efficiency on the water side. This is because the amount of energy given from the heater for a system with low heater efficiency will vary a lot depending on the water flow. For example for a 70/30 system will have the heater efficiency η=0,57 and a 70/60 system will have η=0,14. 70/30 means that the temperature of the ingoing water is 70° C and the outgoing water is 30° C. Both for the inlet air of 0°C and supply air of 20°C. For small changes when the water flow are small the changes in energy will rise very quickly and make it harder to efficient regulate the demand of water flow. For the 70/30 system, the changes in output energy will be more constant than in the 70/60 system. Because of this it is better to use air heaters with higher efficiency. [1]
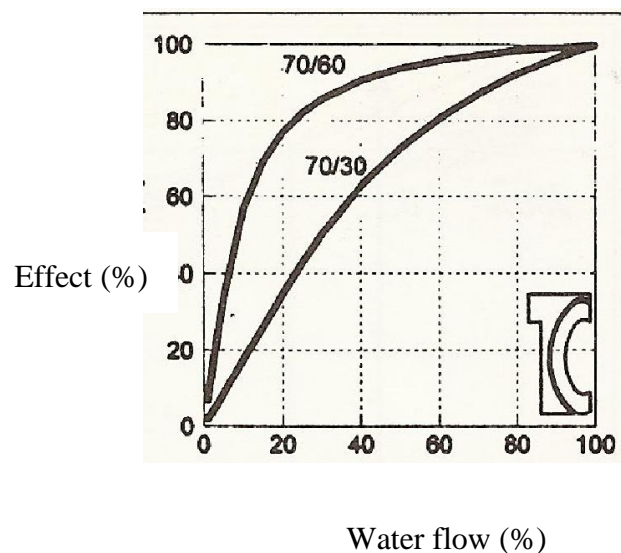
Effect (%)

Water flow (%)

Figure 5. *The heat effect given off as a function of water flow for a 70/60 and a 70/30 system.* [1]

Heater efficiency on the water side is defined as $\eta_w = \frac{t_{w,in} - t_{w,out}}{t_{w,in} - t_{a,in}}$ [11]   (1)

Where: η_w = Air heater efficiency on the water side [-]

$t_{w,in}$ = Water inlet temperature [°C]

$t_{w,out}$ = Water return temperature [°C]

$t_{a,in}$ = Input air temperature [°C]

For a 2-pipe distribution system, it is possible to use variable flow. It is also possible to place smaller pumps along the system. See Figure 6. If that is done all pumps can be smaller. The first pump then does not need to provide pressure for the whole

system from the pump to the last heater. Instead the other pumps can create more pressure during the way. When the demand for water is not at maximum and the first pump can provide pressure for the whole system, the other pumps can shut down. In this system energy for pumps can be reduced because of that the pumps can then run at speeds where their efficiency is as high as possible. This system also makes it more stable and reduces the variations in the pressure losses. One drawback with this is that a lot of small pumps generally has a lower efficiency than larger pumps and thereby demands more energy [4]. In later time, the pumps have however gotten a much better efficiency compared to older pumps. The efficiency of small pumps is now up at around 40 percent compared to the old pumps with an efficiency of around 5 percent. [2]
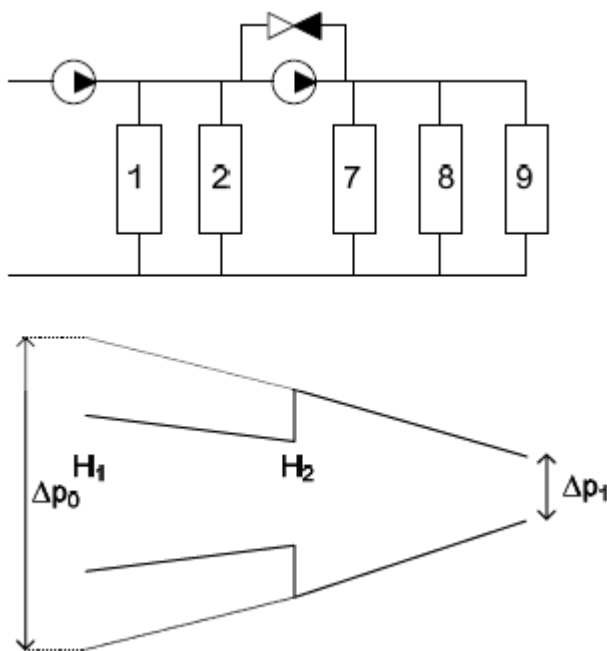
Figure 6. *Example of using a 2-pipe distribution system with more pumps in the system.* [4]

It is however not a good solution to use a variable flow system in a 3-pipe distribution system. This is because it will be large pressure drop differences over all heaters at low flows compared to the designed pressure drop. [4]

To regulate a flow one could use either; valves that cuts the pressure or creating the "right" pressure direct by using a speed controlled pump. [6]

2.3.1 Flow control using valves

In this kind of system the output energy is controlled by the water flow instead of temperature regulation. See Figure 7. Because of this the shunt group can be removed. The water flow is controlled by using valves. The pressure from the pump needs to be adequate large to ensure the function over the valve. In this system the flow will, most of the time, be lower than in a system with a constant flow. [6]
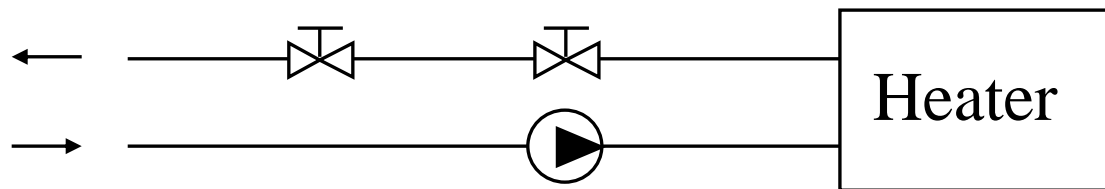
Figure 7. *System using valves for flow control. Made from drawing from "Markusson C., 2009. Effektivisering av pump- och fläktdrifter i byggnader – Elanvändning och systemlösningar".*

2.3.2   Flow control using pump

In this system design the valves for controlling the flows has been removed. See Figure 8. The flow is however the parameter used for controlling the energy output. To achieve this, the pump is the only component used to control the flow. The advantage of this is that the energy for powering the pump is reduced and the system is simpler. It is also simpler to change the system in the future if there is a need to add or to remove components. [6]
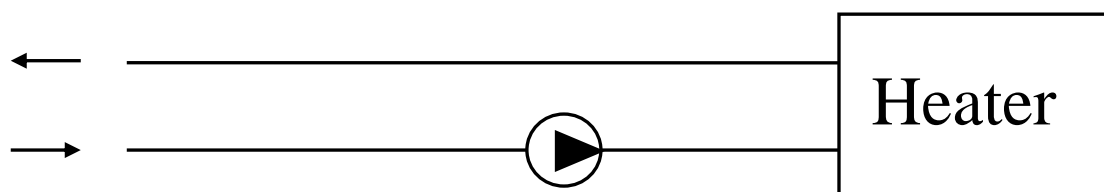
Figure 8. *System using pump for flow control. Made from drawing from "Markusson C., 2009. Effektivisering av pump- och fläktdrifter i byggnader – Elanvändning och systemlösningar".*

The figure below shows the energy consumption in a test with a constant flow, flow control using valves and flow control using pump. [2]
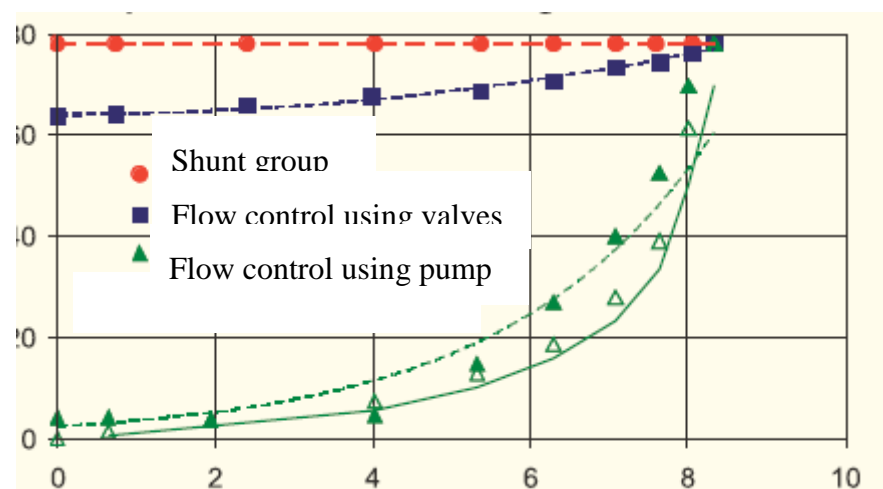
Figure 9. *Pump effect as a function of heating effect for the three different systems.* [2]

2.4   Example

This is an example of the influence of accuracy in regulation of flow and temperature with an 80/40 system with 3 °C error and 10 % error on the water flow. See appendix 2

$$t_1 = inlet\ temperature = 80°C$$

$$t_2 = outlet\ temperature = 40°C$$

$$\Delta t = temperature\ variation = 3°C$$

$$\dot{M} = water\ flow = 1\ kg/s$$

$$\Delta\dot{M} = water\ flow\ variation = 0,1\ kg/s$$

$$Q = \dot{M}c\rho(t_1 - t_2) = 1 \cdot 4,2 \cdot (80 - 40) = 168\text{kW} \tag{2}$$

$$Q = c\rho \cdot \left(\left|(t_1 - t_2) \cdot \Delta\dot{M}\right| + \left|\dot{M} \cdot \Delta t\right|\right) = 4,2 \cdot (|(80 - 40) \cdot 0,1| + |1 \cdot 3|) = 29,4\text{kW} \tag{3}$$

$Q = 168^+_-29,4$ That is equal to a percent different of $^+_-5,7$ %

In other words, an 80/40 heating system where the temperature can vary up to $^+_-3°$ C and the water flow can vary up to $^+_-0,1$ kg/s the heat output of a heater can vary as shown in Figure 10.
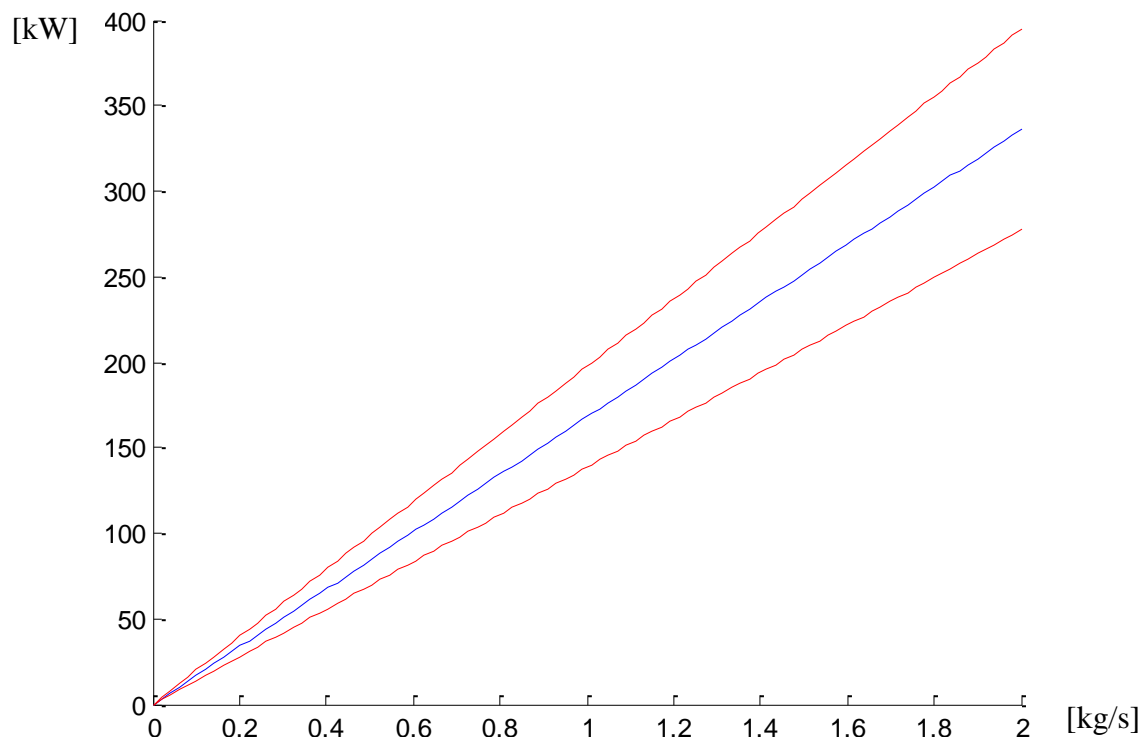
Figure 10. The maximal systematic error. The energy output as a function of mass flow for a system with 3 degrees difference and a flow error of 10 %. For an 80/40 system.

For an 80/40 heating system where the temperature can vary up to $\pm 2^{\circ}$ C and the water flow can vary up to $\pm 0{,}05$ kg/s the heat output of a heater can vary as shown in Figure 11.
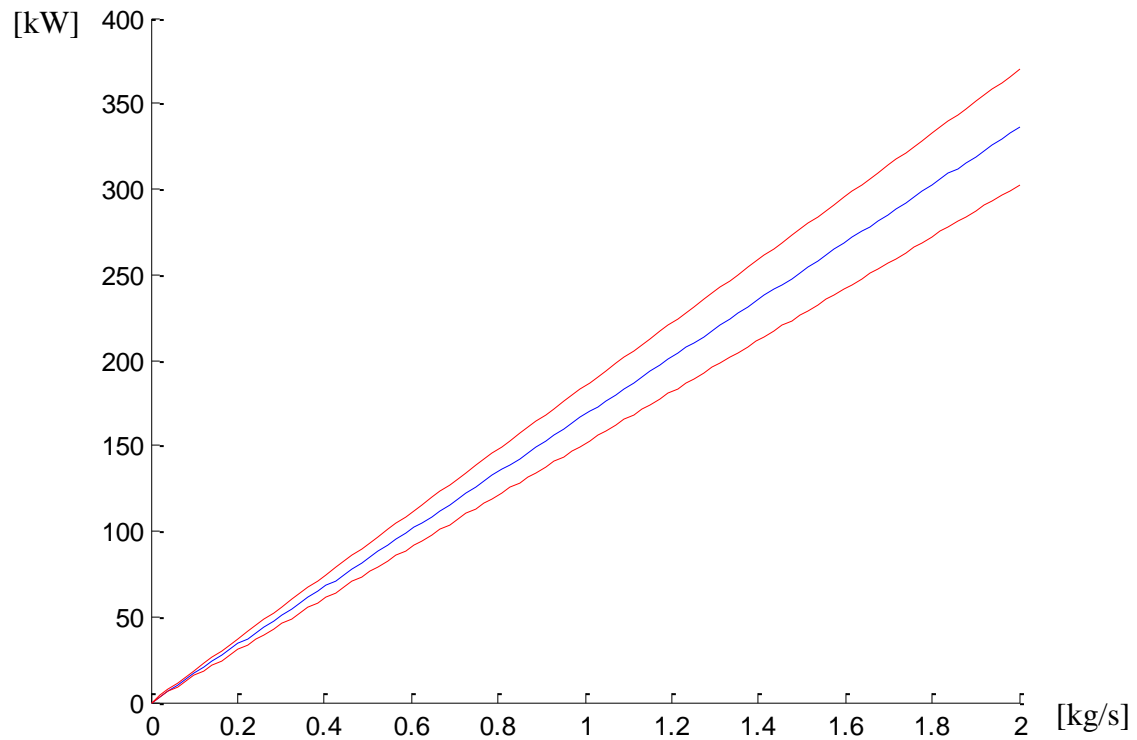
Figure 11. *The maximal systematic error. The energy output as a function of mass flow for a system with 2 degrees difference and a flow error of 5 %. For an 80/40 system.*

3 Components

This chapter looks at the different components used in a hydronic heating system. General knowledge about valves, heaters and pumps are studied. A deeper research on pumps is included in this chapter.

3.1 Characteristic of Valves

This chapter looks at the general function of valves.

3.1.1 General theory

Regulating a flow can be done by using control valves. There are different types of valves that work in different ways. A valve can be described using the two concepts; valve characteristic and valve authority.

The valve characteristic, k_v value, is the relationship between the amount by which the valve is open and its capacity (m^3/h). A 0 % valve opening is fully closed and a 100 % valve opening is fully opened. Different valves can behave in different ways. The two most used valves are the so called linear and logarithmic valves. The linear valve behaves as its name say linear, in other words a change in the valve will give the same percentage change in the k_v value. A logarithmic valve will however get a different percentage change in its k_v value depending on how open the valve is [11]. See Figure 12.
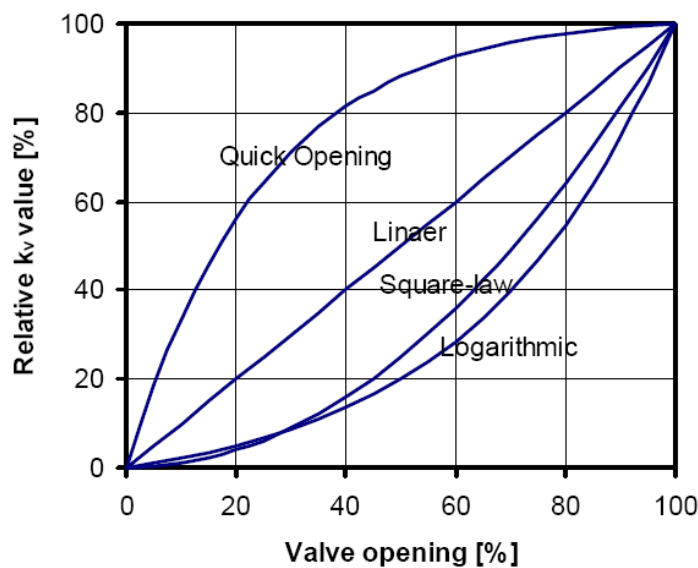
Figure 12. *Valve characteristics for some different valve types.* [12]

Valve authority shows the differential pressure across a control valve when it is fully opened divided with the differential pressure when it is fully closed. This means that the valve authority varies between 0 and 1. [11]

Valve authority is defined as: $\beta = \dfrac{\Delta P_{fully\ open}}{\Delta P_{fully\ closed}}$ [11] (4)

Where: $\Delta P_{fully\ open}$ = Pressure drop when fully open

$\Delta P_{fully\ closed}$ = Pressure drop when fully closed

Mechanical characteristic — **Valve authority** — **True characteristic**

Figure 13 graphs: Mechanical characteristic (Relative k_v value [%] vs Valve opening [%]), "and", Valve authority (Relative flow [%] vs Relative k_v value [%], β = 0.25, β = 0.1, β = 0.5, β = 1), "give", True characteristic (Relative flow [%] vs Valve opening [%], β = 0.25, β = 0.1, β = 0.5, β = 1)
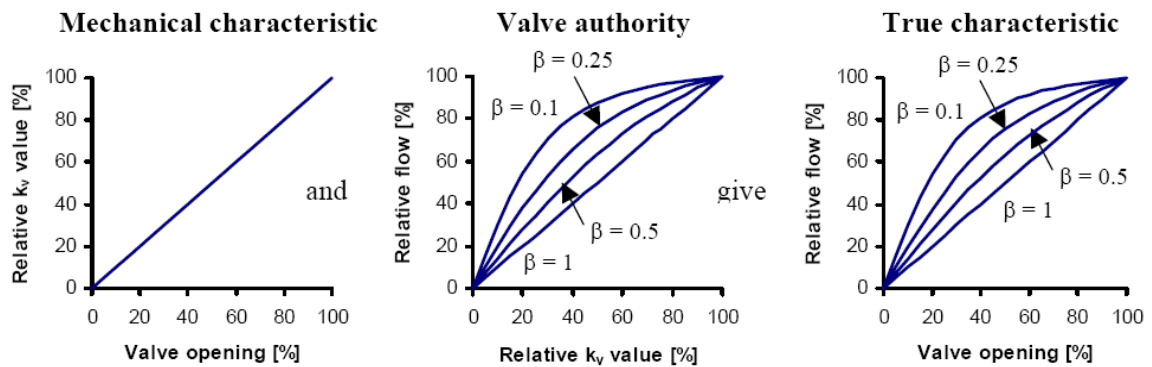
Figure 13. *The effect of both the mechanical characteristic and the valve authority has on the flow on a valve on a linear valve.* [11]

Figure 14 graphs: Mechanical characteristic (Relative k_v value [%] vs Valve opening [%]), "and", Valve authority (Relative flow [%] vs Relative k_v value [%], β = 0.25, β = 0.1, β = 0.5, β = 1), "give", True characteristic (Relative flow [%] vs Valve opening [%], β = 0.25, β = 0.1, β = 0.5, β = 1)
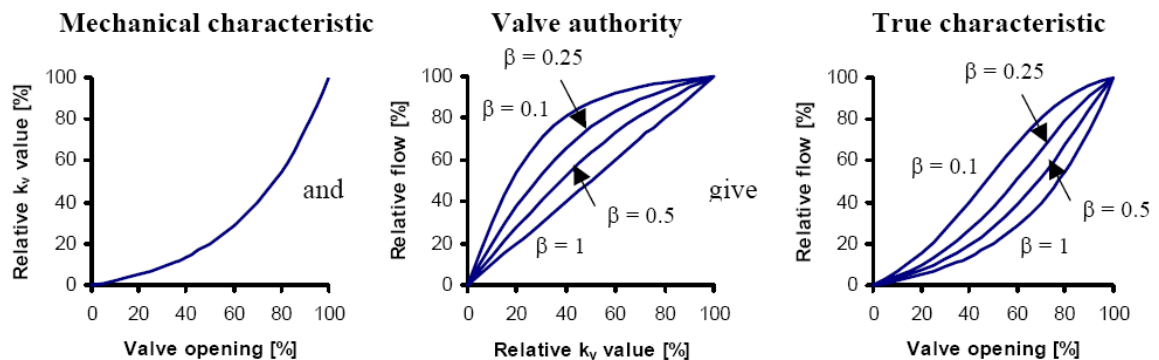
Figure 14. *The effect of both the mechanical characteristic and the valve authority has on the flow on a valve on a logarithmic valve.* [11]

A valve with a low valve authority will because of this change very little in the flow of the liquid when the valve begins to close. It therefore requires a smaller opening of the valve to get a lower flow than it requires when the valve is almost closed. For a valve authority of 1 is on the other hand much "better" since it could better control the flow in accordance with the mechanical characteristics. It must be said that a value of 1 is very hard to achieve and is more of a theoretical value. [11]

3.2   Characteristic of heaters

This chapter looks at heaters and their general function. General knowledge such as low/high flow, low/high temperature and heater characterization will be studied.

3.2.1   General theory

A system with a low average temperature is said to be a low temperature system, while a system with a high average temperature is called a high temperature system. Usually systems are written as e.g. 80/40 system. That means that the supply temperature is 80 °C and the return temperature is 40 °C. High flow system uses, as its name says, a high water flow. The opposite goes for the low flow system. [11]

The high flow systems are the most used system in hydronic heating systems and are more commonly used in the constant flow systems rather than in flow control systems. The building norm at new constructions is to use a 55/45 system with high flow. An advantage with high flow systems is that they are stable and insensitive to disturbance in the flow. They are however not as flexible when changes in the design is being made in heating demand or heating source. [8]

The low flow system is more easily designed in flow control systems. The low flow system is compared to the high flow system more flexible when it comes to changes in the system design. They are, however, more sensitive to a correct flow in to the system. Generally, the low flow system demands less energy to power pumps compared to a high flow system and thereby is less energy consuming. [8]

In order to get the same output of energy; the low flow system demands larger temperature differences than in a high flow system. It is also possible to use much larger heaters in order for them to give off more heat. This is because the temperature falls more as the water passes thru the radiator. The higher the flow rate is the more heat power is released thru the radiator. At lower flows the output energy is increasing more rapidly than it does during changes of flow at higher flows as seen in Figure 15. [11]
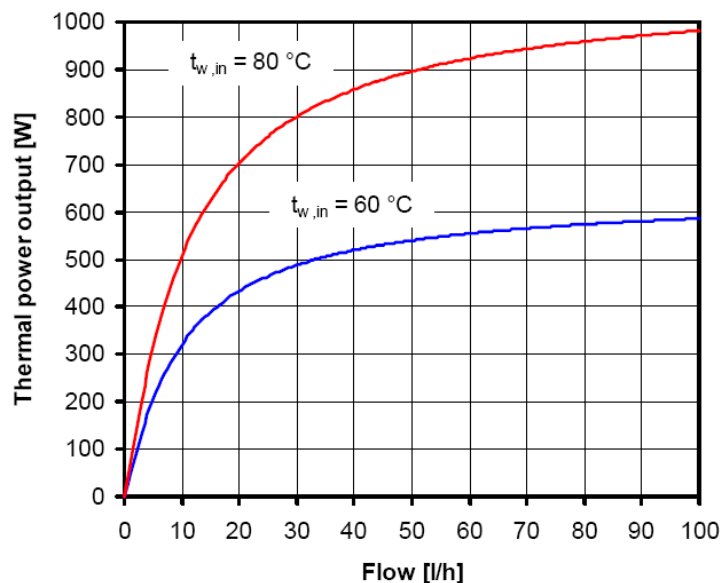
Figure 15. *Flow characteristic of one radiator with two different temperatures.*

Figure 15 also shows that for a higher inlet temperature, the heating power is larger than for the lower inlet temperature. It is however possible to get the same heat release by increasing the flow up to a point. It would also be possible to use the lower inlet temperature and a larger radiator in order to give of the same heat as the higher inlet temperature. [11]

The heat released from a radiator: $\dot{Q}_{rad} = K_{rad} \cdot \Delta t_m{}^n$ [11] (5)

Where: $\dot{Q}_{rad}$ = Thermal output from radiator [W]

K_{rad} = Radiator constant [W/°C^n]

$\Delta t_{m=}$ Mean temperature different

n = Radiator exponent [-]

K_{rad} and n is depending on the size and design of the radiator. [11]

When heating with air heater; warm water, oil or steam is often used to transport heat power to the heater. The substance flows thru pipes either in the same direction as the air goes or the more effective way, in the opposite way as the air. The substance cannot flow to fast; otherwise it might harm the pipes. If the air heater uses steel pipes the maximum flow of 3 m/s should not be exceeded. [3]

The energy output from an air heater depends a lot on the air flow passing thru the device. The equation for the radiator is therefore too simple. Therefore the efficiency of a heater is defined as:

$$\eta_a = \frac{t_{a,out} - t_{a,in}}{t_{w,in} - t_{a,in}} \text{ for the air side and } ^{[11]} \qquad (6)$$

$$\eta_w = \frac{t_{w,in} - t_{w,out}}{t_{w,in} - t_{a,in}} \text{ for the water side } ^{[11]} \qquad (7)$$

Where: $t_{a,out}$ = Output air temperature [°C]

$t_{a,in}$ = Inlet air temperature [°C]

$t_{w,in}$ = Water inlet temperature [°C]

$t_{w,out}$ = Water return temperature [°C]

If the flow is changing, so will the efficiency. Therefore the heat release from the heater will also change. [11]

3.3   Characteristic of Pumps

This chapter presents both the general knowledge and a deeper study on how pumps can work in a flow control system.

3.3.1   General theory

This chapter gives the basic theory on how pumps work.

A pump in a heating circuit is used to circulate water and to compensate for the pressure losses that occurs in the system. Each pump has a pump characteristic that is unique for that pump. The pump characteristic describes how much pressure the pump can give as a function of water flow. The system characteristic is the relationship between the flow and the pressure loss in the circuit. At the point where the two lines meet is called the operating point. This point is where the pressure rise of the pump is equal to the pressure loss of the circuit at a specific flow [11]. See Figure 16

As the pressure drop in the system is changed, the system characteristic will change. Because of that, the operating point will change. If the pressure drop in the circuit is increased; the flow from the pump will then decrease if the speed of the pump is unchanged. [11]
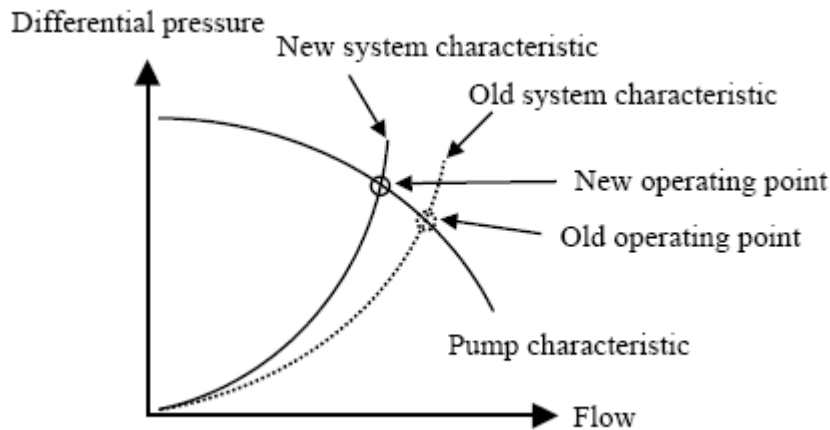
Figure 16. Picture showing the pump characteristic of a pump and what happens if the pressure loss from the circuit is increased. [11]

The pump characteristic can be a steep characteristic, meaning that the pressure generated from the pump is changing fast as the flow is changing. It can also be a flat characteristic which means that the pressure from the pump quite slowly changes as the flow changes [11]. Some pump can also change its rotation speed and can thereby adjust to its current demands. A so called variable speed pump can then, when possible, reduce its pressure gain and thereby reduce the pump drive power required for the pump. [7]

3.3.2 Possibilities to regulate with pumps

This chapter looks at the possibility to use pumps for heating systems. It looks how pumps can be controlled. It therefore looks at information from pump manufacturer Wilo.

Correct used pumps have the potential to save a lot of energy. For instance the pump Wilo-Stratos PICO has only a minimum energy consumption of 3 W and compared to convention unregulated pumps it can save up to 90 % energy according to Wilo. [14]
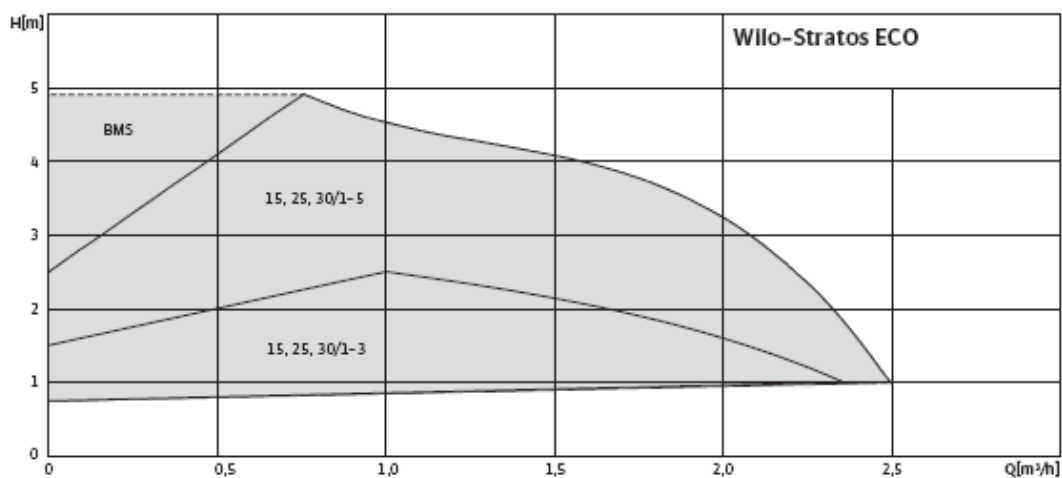
Figure 17. Pressure from the pump over flow for Wilo – Stratos ECO[12]

Pumps can be regulated by on/off functions, meaning that they are either turned off or they are running in a predefined speed. This can for instance be used when the flows in the systems are constant. It is since the 80s also possible to adjust the power on a pump without using any step changes. It is done by electronic frequency converters. This means that a frequency is sent to the pump and the pump will then adjust its speed depending on the size of the frequency. The frequency can be set without any steps. The pump itself can then also change its speed without any step changes. The frequency can however not normally be set to be below 20 Hz. Some pumps can work at as low as 16 Hertz. This is due to motor technical reasons. This means that the pump can't work at lower than 40 % of its maximum speed. [5]

When controlling the flow of the pump, in a flow control system, it could be regulated by using mainly three different ways. The first way is for the pump to generate a constant differential pressure of the differential pressure setpoint Hs, See Figure 18, as the water flow changes. This is done until it reaches the maximum pressure as the pump can generate for that flow. The second way is to let the differential pressure be variable. In this way the pressure is changing depending on the flow. It can for instance be set to be linear relationship between ½ Hs and H as Figure 19 shows. The third way is to let the pressure depend on the temperature. See figure 20. The pump then measures the temperature of the liquid and then changes the speed. [13]
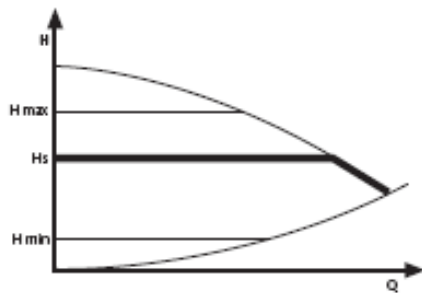
***Figure 18**. Control mode with constant differential pressure over flow* [12]
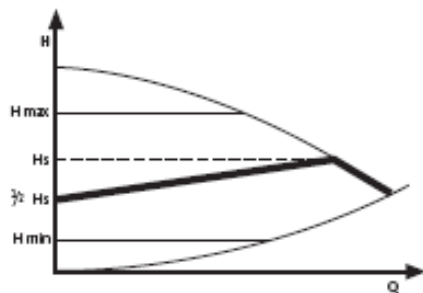
***Figure 19**. Control mode with variable differential pressure over flow* [12]
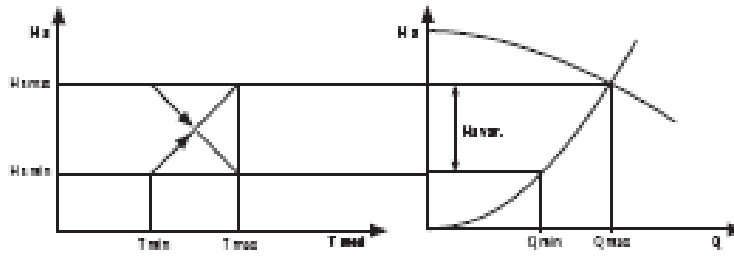
Figure 20. Control mode with pressure depending on temperature [12]

3.3.3 Design criteria's

This chapter looks at the possibility to use pumps for heating systems. It looks design criteria's for the pumps. It therefore looks at information from pump manufacturer Wilo.

As mentioned in a previous chapter it is possible to use more than one pump in a system. When the demand for heating is low only one pump is operational. When the demand for more heating water than one pump can provide, the second pump is set to work. They can also both set in to run at the same time if the energy consumption of both pumps is lower than just to run one pump. [12]

The pumps efficiency (η) depends on the flow of the liquid. See Figure 21. At what flow the best efficiency happens depend on what type of pump it is. When choosing pump heating system it is therefore important to know at what flows the system normally operates in and chose a pump with its highest efficiency in that range. [13]
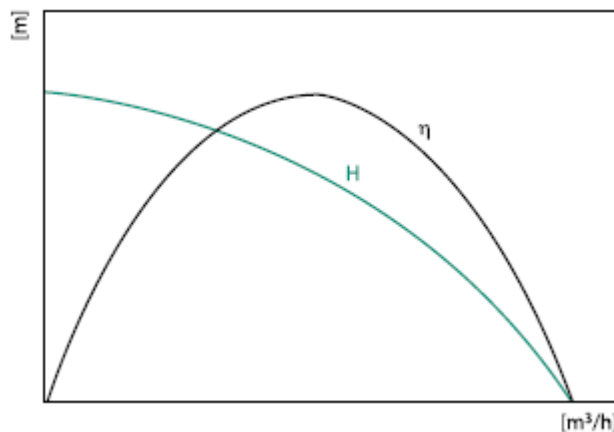
Figure 21. An illustration of how the pump efficiency (η) *varies as a function of flow. It is plotted in the same figure as a pump curve* [13].

When the flow in a pipe decreases the pressure loss will also decrease. The pump can then work with a lower pressure and the energy consumption will decrease if the pump is controlled. [13]

Cavitation in a pump is when vapour bubble formats in the pump. To prevent this, an over pressure is needed at the pumps suction port in relation to the vapour pressure of the fluid being pumped. For Wilo-stratos ECO the demand for minimum suction is then 1 m at temperature of 50°C, 3 m at 95°C and 10 m at 110°C. These values needs

to be increased as; the temperature increases, density decreases, if the flow resistance on the pumps suction side increases and if there is a lower atmospheric pressure. [12]

The pumps also require a minimum flow rate to ensure the function of the pump. The reason for this is that if the flow is zero the pump can overheat if it is working. [12]

The sound pressure level from the pumps depends on the speed of the pump. The less water flow that is required for a heating system the less noise the pump will give off. See Figure 22 for the sound pressure level over the pumps rate motor output. [12]
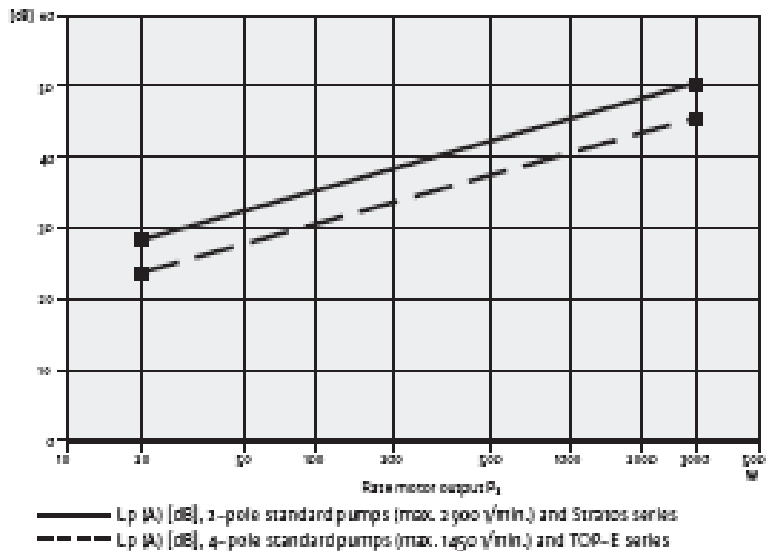
Figure 22. Sound pressure level over the pumps rate motor output [12]

4 Case study on pumps

This chapter is about an experimental study that illustrates the different ways a pump can work for a heating system. It also shows the different pump power demands that are required for the different ways the pump can work.

In the experimental study, a rig is used. On that rig, it has measurement equipment for measuring the water flows, the differential pressure and the pump drive power. In order to pump the water, the rig has two different pumps. One pump is a constant speed pump that can be set to work at three different speeds. The second pump is a controlled pump. Its speed is controlled as a function of flow. It creates a desirable pressure increase. It works at three different settings. How those three settings work will be presented in the result.

The purpose of this experimental study is to determine how a certain type of unregulated as well as controlled pumps works. It is also to see how the pump drive power consumption changes for the two types of pumps as the flow changes.

The aim of this task is to determine the relationships between flow, pressures and energy consumption of different types of pumps. By measuring the flows, pressures, and energy consumption for two different pumps, this experimental study will give a good knowledge on how both unregulated as well as on how controlled pumps works.

4.1 Task

This chapter contains information on how the experimental study was carried out.

In order to do the experimental study on the two pumps, the rig was prepared: it was filled with water and all the air in the rig was removed. The pressure was also increased to 1 bar which is the standard pressure level for heating systems less than 10 m high.

In Appendix 3, one can see the different steps in conducting the experimental study.

See Figure 23 to see the position of the various components.

a) Energy use

b) The equipment for measuring the pressure difference in the system

c) The equipment for measuring the flow in the system

d) The connection to measure the differential pressure

e) This should be closed in the second part, and open in the first part

f) This should be open in the second part, and closed in the first

g) These valves should be closed during the first experiment

h) Valve

i) With this valve the pressure loss in the system can be increased

j) The connection to measure the differential pressure

Figure 23. *The rig used in the laboratory work*

Part 1

The first part of the experimental study was to gradually change the opening of the valve and thereby changing the system curve. A number of operational points for the rig were then being found for the unregulated pump. By doing this the pump curves of the pump was found. The power usage of the pump was also analyzed.

The pump was set on the first constant speed and the valve was in the beginning open. Because of the water flowing inside the rig, pressure losses occurred that needed to be compensated by the pump. Due to that the speed of the pump was constant; a balance between the flow and the differential pressure occurred that was measured. This point is called the operational point. The valve was then gradually closed and thereby created a greater pressure loss which in turn resulted in a new operational point. The flow and pressure rise was read off and plotted in order to find the pump curves. The

power usage for each of these points was also measured in order to see how much power the pump needed as the flow changes.

The speed of the pump was then changed and by the same procedure as before, new pump curves could was found and plotted.

Part 2

The second part of the laboratory was to find how the rig worked when using the controlled pump. It consisted of three different settings. This part was therefore to see how the different settings worked. The power usage for the pump was also analyzed.

In order to do this, the pump was set to one setting and just as the previous part the valve was first opened and then gradually closed. The operational points were read for each time. The difference between this part and the previous part was that this pump is controlled. This means that the speed of the pump will automatically be changed as the pressure loss from the valve is changed in order to achieve a certain operation predetermined by the setting. The three different settings each represent one programming on how the differential pressure should be changed as the flow changes. By plotting the different operational point, one could see how these settings works. The power usage for each of these points was also measured in order to see how much power the pump needed as the flow changed for the specific setting.

The pump was then set to a new setting and the same procedure was done.

4.2   Results

Part 1

From the experimental study the following results are made for the first part of the experiment. In Figure 24 and 25, both the pump curves and the pump energy usage for the pumps are plotted against the flow. Trend lines have been inserted in order to show the characteristics of the graphs and to even out measurement uncertainties.

Se Appendix 4 for all the measured values.
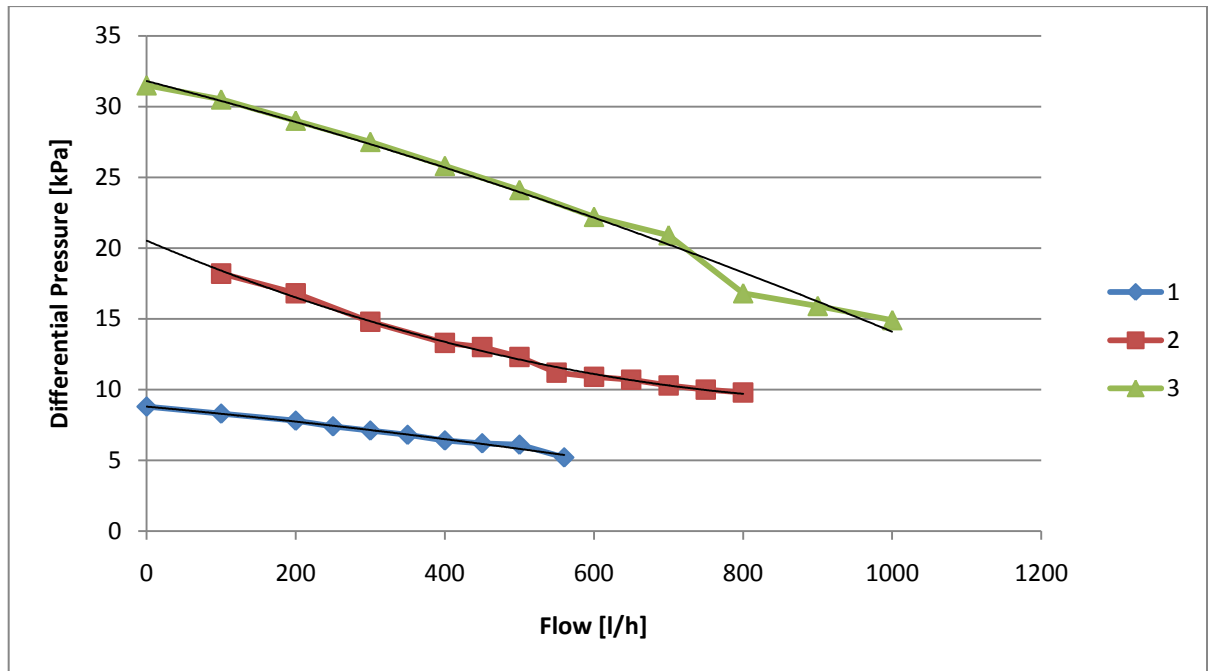
Figure 24. *The pump curves for the first laboratory. The three different curves are the three different speeds of the pump. The curve numbers of each of the curves can be read to the right of the curves.*
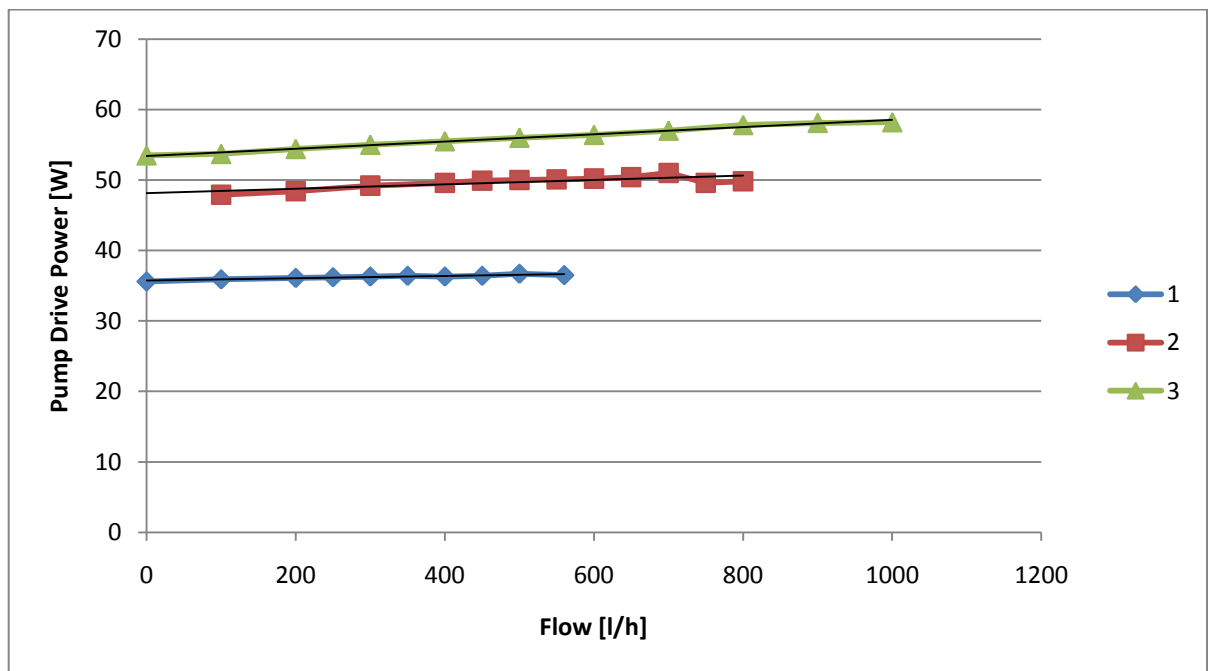
Figure 25. *The pump power consumption for the first laboratory. The three different curves are the three different speeds of the pump. The curve numbers of each of the curves can be read to the right of the curves.*

One can see that the pressure rise of the pump decreases as the flow increases. That is normal for pump curves. The second curve looks like it is turning upwards. That is

probably because of measurement deviations or since the pump is non-ideal. Normal pump curves are usually parable formed as pump curve 1 and 3 looks like.

The power usage of the pump also increases slightly as the flow increase. That is a typical behavior for these kinds of pumps.

There are also some points that deviate from the trend lines. The reasons for that will be analyzed in Chapter 6.

Part 2

For the second part of the laboratory, the operational points are plotted in Figure 26 and the power usages are plotted against the flow in Figure 27. Also in this part trend lines are plotted.

Note that the setting names in the pump are called 1, 3 and 5 because that is what they are called on the pump.
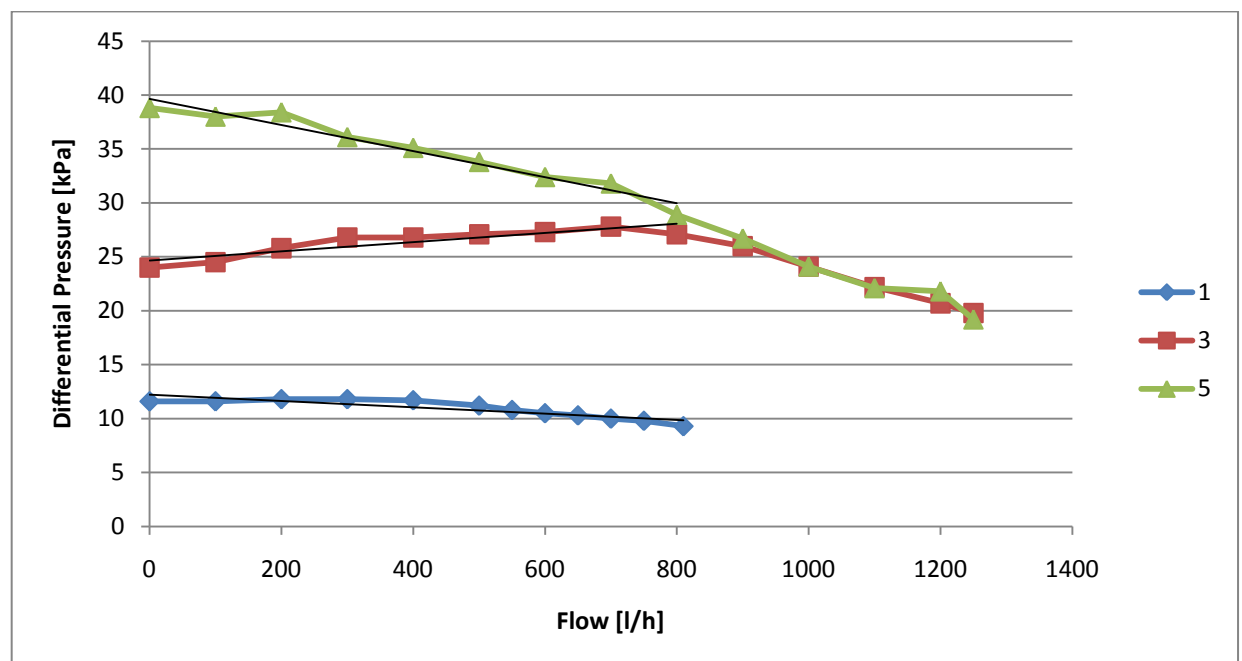
Figure 26. The pump curves for the first laboratory. The three different curves are the three different settings of the pump. The curve numbers of each of the curves can be read to the right of the curves.
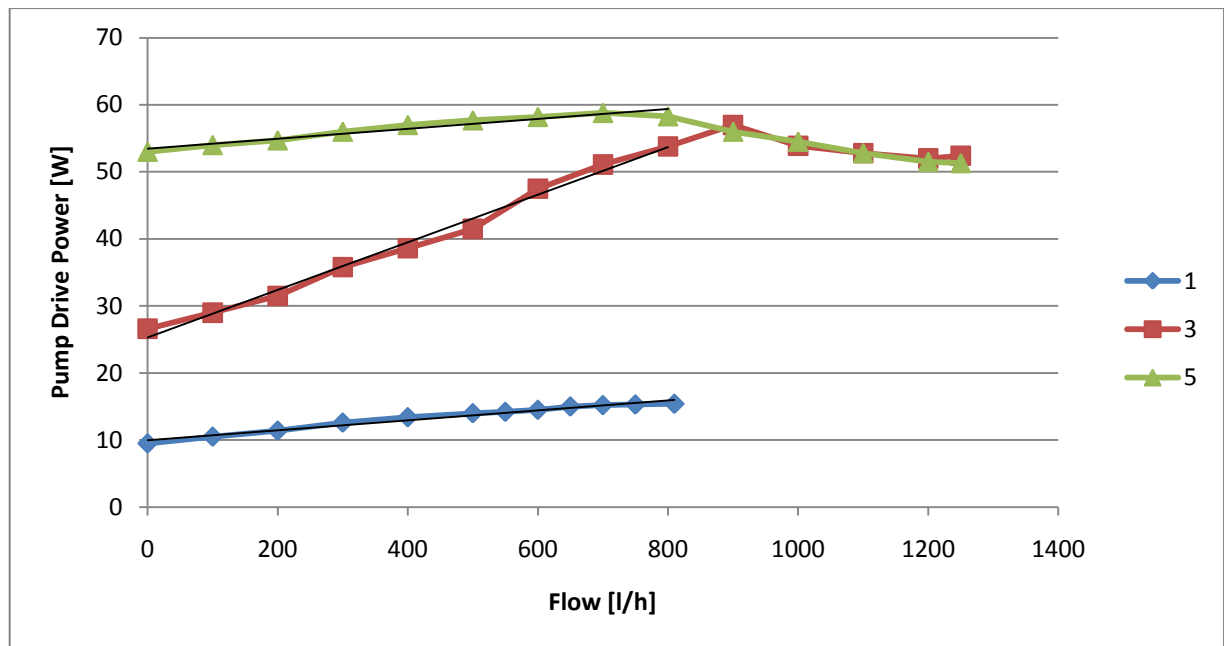
Figure 27. *The pump power consumption for the second laboratory. The three different curves are the three different settings of the pump. The curve numbers of each of the curves can be read to the right of the curves.*

One can see that the three different settings of the pump behave in three different ways. The first one seems to stay at a constant pressure level as the flow changes. It does that by constant changing the speed of the pump. It is, however, hard to analyze that setting due to that it is fist constant and then decreasing. It could be just measurement deviations. With the third setting seem to have a fix relation between increase of pressure and flow. The fifth settings seem to do the opposite. They do that until they reach a flow of around 800-900 l/h. After that flow, the pump can no longer run at a faster speed. In other words, the pump is running on its highest speed. When this has happened, the pump can no longer produce as much pressure change as the system needs. Even thou it can continue to increase its water flow but it can't also increase the pressure.

The reason why these settings exist is because different systems behave in different ways. For a heating system, the flow resistance in a pipe increases as the flow increases. If one wants a constant pressure level over a heater as the flow increases, something needs to compensate for the increased pressure resistance in the pipes. By letting the pump create a gradual increasing pressure level as the flow increases, the pump can compensate for this pressure resistance in the pipes. The heater will then get a constant pressure level even when the flow is changed. The setting when the pressure was kept could be used when the pressure losses of the pipes are negligible as the flow changes.

The energy savings, by letting the pump regulating the flow, is quite high. That is especially the case for the third setting. At its highest flows, the third setting uses around 50-60 W. When the flow is lower the pump uses only as low as 25 W. That is a large reduction of energy usage compared to when the flow is at maximum. For a constant flow system, it would have used maximum power at all time. A variable flow

system would only use half of the power usage when the flow is close to zero. Therefore the energy savings are large when the flow is low, but for when the water flows are large it does not matter.

In this part of the task the results are also fluctuating a bit as in the first part.

5   Case study of using flow control

The purpose of this chapter is to look at the possibility to use flow control in reality and to see what limitations it has and what its possibilities are. This chapter will study real heating circuits in order to see if it is possible to change a system into flow control system.

Contact with heating circuit designer, was made in order to get information on the heating circuit that is to be analyzed in this chapter.

The heating circuit to be analyzed consists of two different types of system; one radiator using a shunt group and a group of air heaters using flow control with valves. See Figure 28.
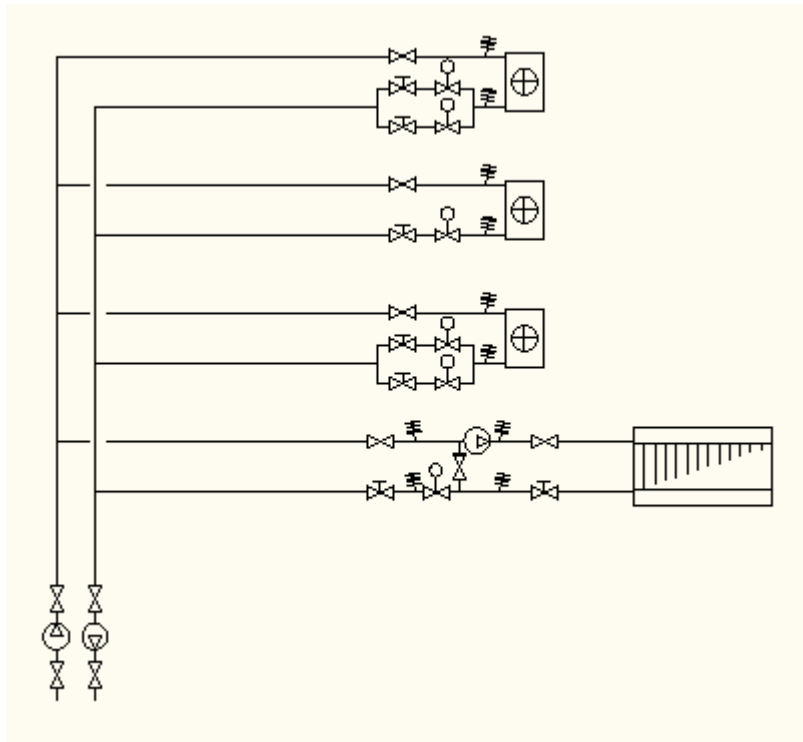
Figure 28. *The heating circuit with both the radiator and the group of air heaters.*

5.1   Description of the circuit using heating batteries

This part looks at the possibility to change the air heater system, using flow control with valves, into:

- A flow control system without valves with just the pump.
- A system using the traditional shunt group.

5.1.1   The present solution of the heating circuit

This heating circuit is a real system being used in a building in Sweden. Only the part of the heating circuit that is going to be analyzed is shown here. It uses the following products:

- The pump used is the brand Grundfos and is controlled

- The valve used is the brand TA
- Heating battery

It uses 3 heating batteries with each having a valve for regulating the flow before the battery. The system also has a pump before and one after the heat exchanger the system is connected to. See Figure 29.
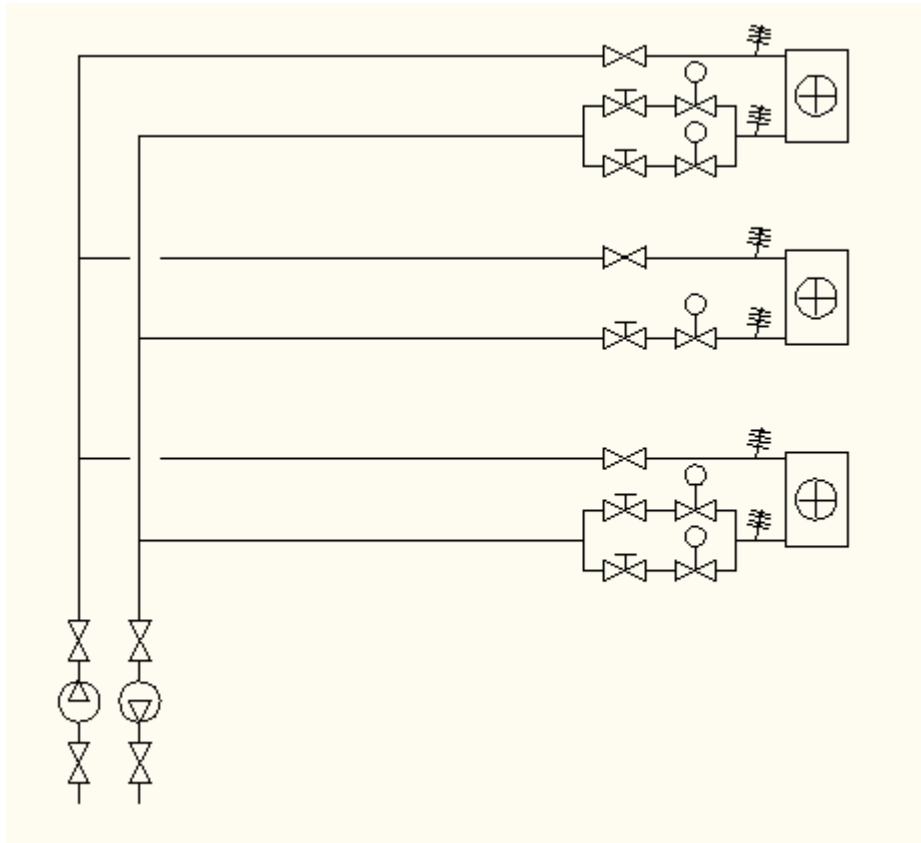
Figure 29. *The system as it looks now.*

5.1.2 A system using the traditional shunt group

This is how the system would look like if it was a constant flow system. See Figure 30. It uses a shunt group in order to regulate the heat power going to the heating battery. It does that by letting water from the heater mix with the new hot water. By measuring the temperature of the water that comes from the heater, exactly how much water that should go around and how much "new" hot water should go to the heater is regulated by the valves. It is also having an extra pump before each battery in order to keep the flow constant. By having a constant flow thru the heater it is simpler to regulate the flow. The pump can also be well dimensioned. In other words, it can be set to work at its most effective speed.
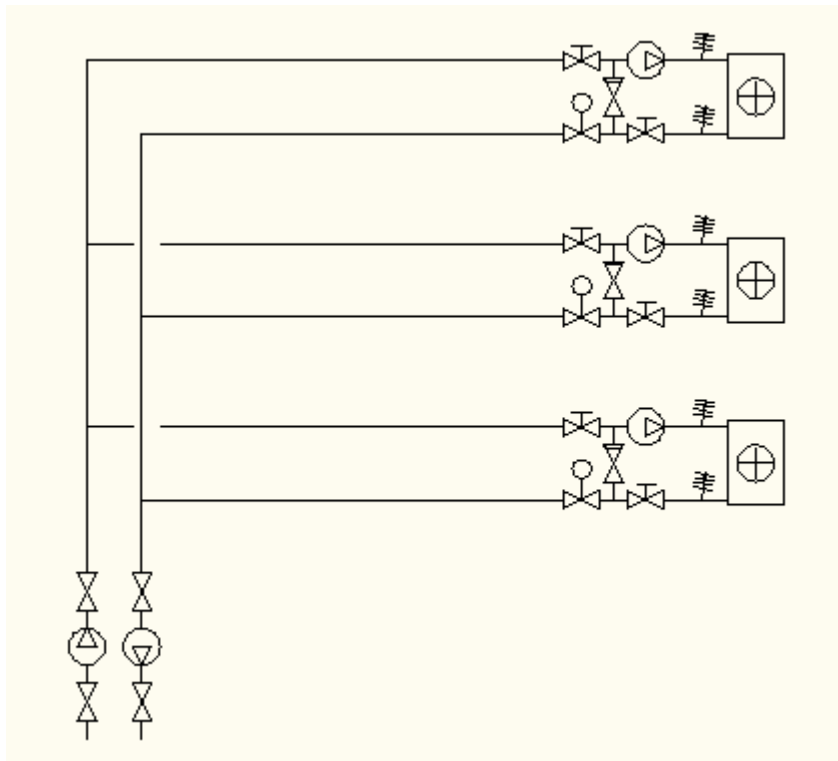
Figure 30. The system using a shunt group and constant flow instead of a flow control with valves

5.1.3 A flow control system without valves with just the pump

This is how the system would look like if it was a flow control system without valves. See Figure 31. It uses just a pump in order to control the flow to the battery. The pumps are controlled pumps that regulate the flows accordingly to how much need for heating there is. Accordingly to how much pressure need there is for the heating batteries, the pumps will create that.
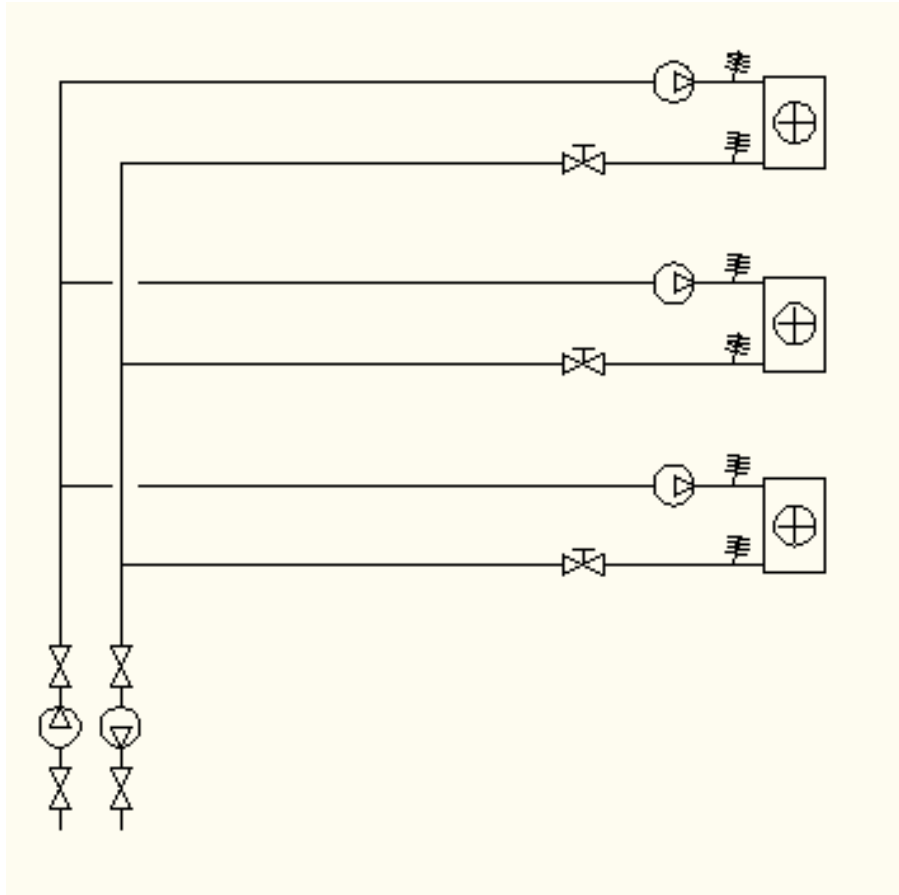
Figure 31. The system to be analyzed using flow control with pumps

5.2 Description of the circuit including radiator

This part will see what happens if a constant flow system is changed into a flow control system. Therefore a system using a shunt group will be changed into:

- A flow control system using valves
- A flow control system using just the pump to control the flow

This project will look at what happens with the different components when the system is changed from a shunt group into a flow control system. Using the data from the different components, studies will be made on if it is possible to use flow control for the whole flow field.

5.2.1 The present solution for the heating circuit

Only the part of the heating circuit that is going to be analyzed is shown here. It uses the following products:

- The pump used is the brand Grundfos and it is controlled
- The valve used is the brand TA
- Shunt group with a pump from Grundfos
- Radiator

It uses a shunt group to control the heat output, and it uses a pump to keep the flow at a constant flow. The system uses a pump after and a pump before the heat exchanger is also used for pumping the water. See figure 32.
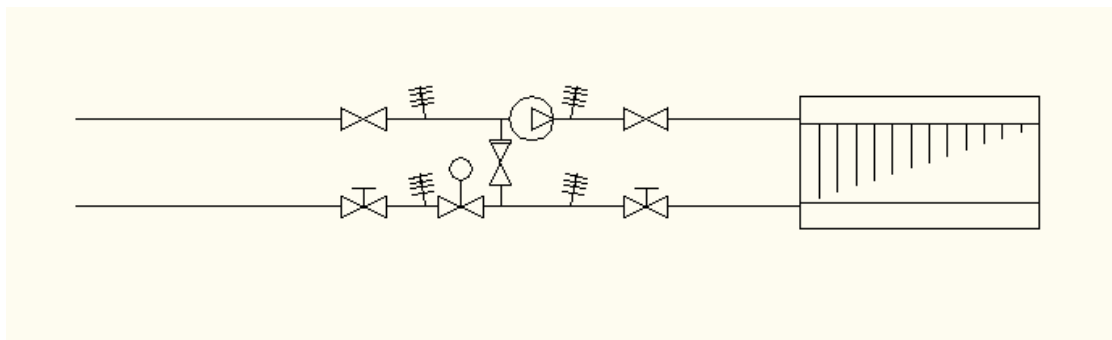
Figure 32. *The system as it looks now.*

5.2.2 A flow control system with valves

This is how the system would look like if it was a flow control system with valves See Figure 33. It uses a flow control with valves in order to regulate the heat output. The flow is regulated by both the controlled pump and the valves. In order to ensure the function of the valve, the pressure needs to be sufficient.
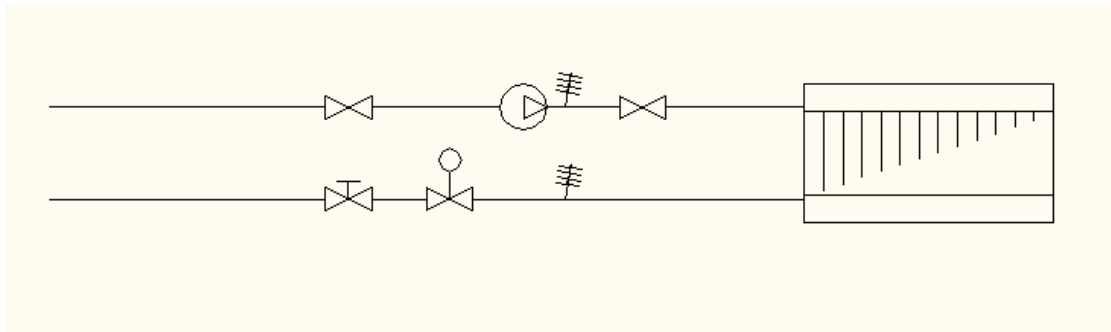
Figure 33. System using flow control with valves.

5.2.3 A flow control system with just the pump

This is how the system would look like if it was a flow control system without valves. See Figure 34. It uses just a pump in order to control the flow to the radiator. The pump is controlling the flows accordingly to how much need for heating there is. Accordingly to how much pressure need there is for the radiator, the pumps will create that.
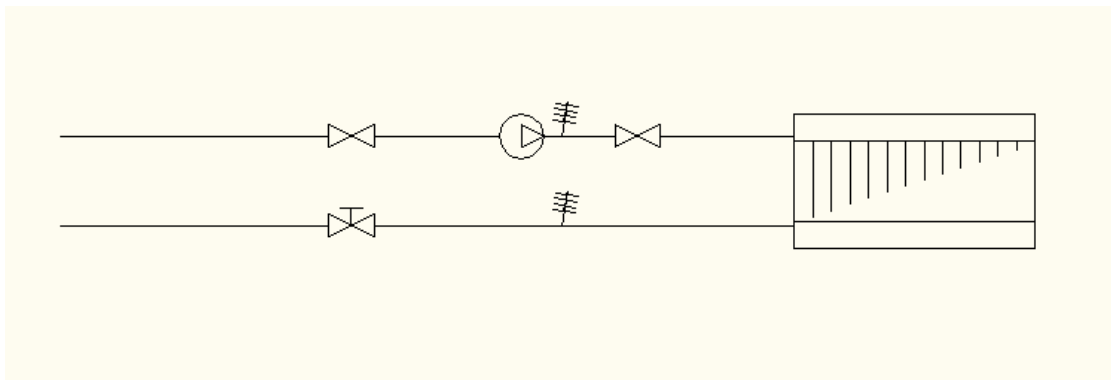
Figure 34. System using flow control with just the pump.

5.3 Consequences of changing system

How the different components works when the system is changed from/to a constant flow system to/from a flow control system. If nothing else is written, the information comes from Petitjean R., 1994. Total Hydronic Balancing – A handbook for design and trobleshooting of hydronic HVAC systems.

If the system is changed from a constant flow system into a flow control system the pumps will not be set to run on its most effective speed. The efficiency, η, of the pump depends on the speed. For a constant flow system the pump that is chosen has its highest efficiency where the flow is intended to be. For a variable flow system, the flow will depend over time. Therefore the pump cannot run at its most efficient speed at all time. The pump power usage does however drop as the flow decreases. This power usage has also the potential to too bee even less if the pressure rise of the pump is lowered. It should also be pointed out that the power for the pump becomes heat as the pump is pumping the water. This heat transfers to the water and is therefore used

in the heaters/radiators. It could therefore be discussed if it is such a good idea to reduce the pump power usage in heating systems.

For a heater, the constant flow system gives a more stable control. We could see from Figure 35 that the constant flow system behaves in a more linear behavior than the variable flow system. The variable flow system gets a more unlinear behavior that is harder to regulate. Therefore the constant flow system through a heating coil will give a more uniform air temperature. It will also give a protection against freezing. The constant flow system does however require one pump for each coil.
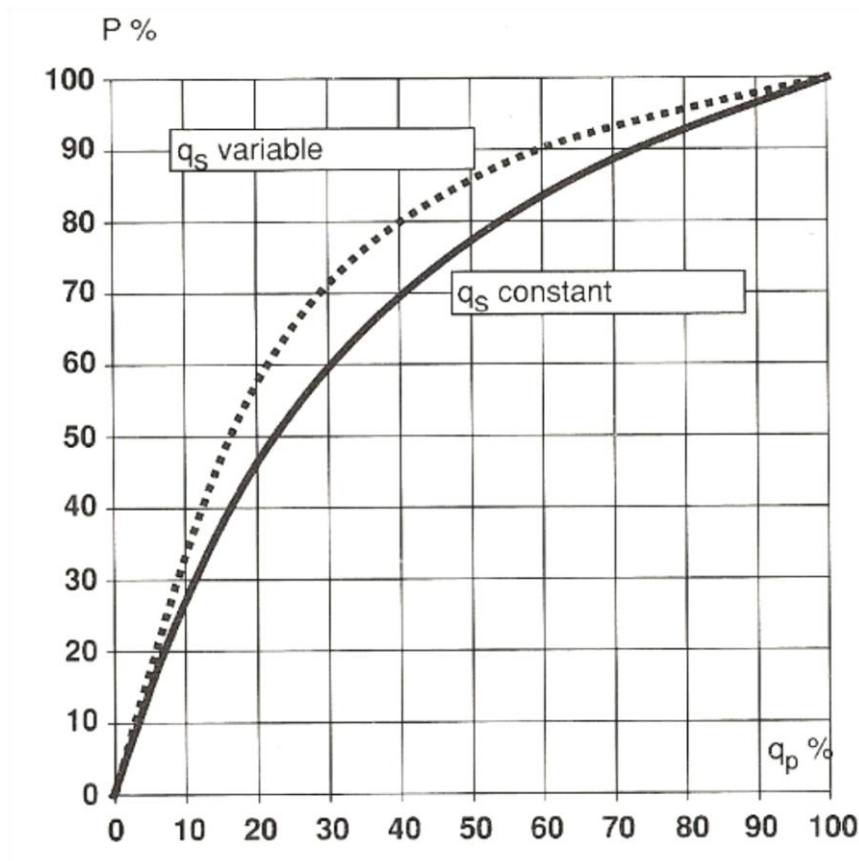
Figure 35. The released heating power in percentage for a constant- and a variable flow system over percentage of water flow on the primary side

When there is a low flow in a heating system, the pressure drop in pipes decreases. The differential pressure in remote components then increases. The authority of the control valves then reduces. If an unregulated pump is used, where the speed is unchanged, the pressure rise from the pump increases as the flow decreases. Both an increased pressure from the pump and a reduced pressure loss from the pipes as the flow decrease therefore increase the differential pressure in the end of a heating circuit. If a controlled pump is used instead, the pump can reduce the speed of the pump and thereby reduce the pressure rise from the pump. The pump can then compensate for the reduced pressure loss in the pipes.
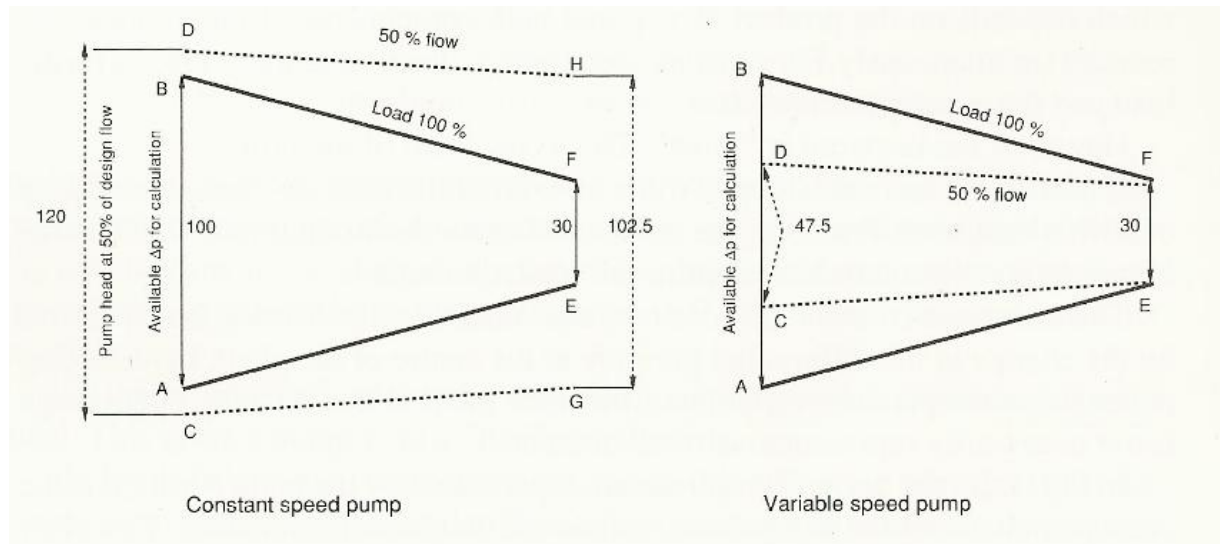
Figure 36. Differential pressure for a constant- and a variable speed pump for 50 % and 100 % flow.

When there is a low flow, the heat losses from the pipes can be substantial if the insulation of the pipes is small. For two different heaters, the temperature could then vary a lot. This could result in that the heaters furthest away from the pump will not get enough heating power if the water flow from the pump is too small. The pump also has a problem to pump too little water. If the flow is too small, the water cannot cool down all the heat produced by the pump. If that happens; the pump can't pump the water properly.

When the flow to a heater is reduced, the water can get a higher temperature drop. In other words the water will get a lower return temperature. This is very valuable in a lot of places. In for example district heating is this valuable. The efficiency of the turbines will increase if there is a low return temperature. There is also useful in normal networks since lower water temperatures means that the heat losses from the pipes reduces.

6 Conclusion

6.1 Summary

Flow control is a way to regulate the heat power to an air heater or a radiator group. It does that by varying the water flow going the heater component. By using flow control instead of a constant flow system, there is a potential to save energy to the pump. It could also get a high temperature difference in the system when flow controlled is used. That is something that is very good in some applications, such as district heating systems.

There are two ways of using flow control; either it could be done by using a pump and valves or it could use just a pump. In a flow control system where valves are used; the pump pumps water and generates pressure and the valve then regulates how much the flow should be. The pump could also adapt its speed to what is necessary. If just a pump is used; the system has a lot of potential to save energy required for the pump.

One advantage of using a constant flow system is that the pump is working at its most effective speed. If a variable flow system is used, the efficacy of the pump and by that the energy consumption will vary as the flow varies.

The speed controlled pump in the study can work at mainly three settings. The first setting is that it generates a constant differential pressure as the water changes. It can do that until its maximum speed. The second way is to let the differential pressure change linearly as the flow changes. It can also change the differential pressure depending on the temperature measured in the system.

Cavitation can happen to a pump. This is when vapour bubble formats in the pump. The way to prevent this is to have an over pressure at the suction port of the pump. These values depend on the temperature of the liquid. The pump can also get overheated. This can happen if the flow is too low to the pump. Therefore; the pump has a lower limit to how much water it can pump. There is also one other problem with low flows; namely that when there is a small flow thru the pipes there is a large heat loss. This heat loss is larger when the pipes are badly insulated and the result can be that the heaters will not get enough heat power to heat.

A heating circuit can use a low flow system or a high flow system. The most commonly used system is the high flow system. It suits a constant flow system very good. The low flow system is good in a flow controlled system. Because of the less water that needs to be pumped, the low flow system requires less pump drive power. In order to get the same heating amount; the temperature differences of the circuit needs to be larger.

A heater in a constant flow system is more stable to control than a heater in a flow control system. The circuit with a constant flow system behaves in a more linear behavior than a variable flow system. Because of this; a heating coil in a constant flow system will get a more uniform temperature.

One problem using flow control is that as the flow decreases; the pressure drop in the pipes also decreases. As a result of that; the differential pressure of remote components increases. This could be solved if a speed regulated pump is being used. If an unregulated pump is used instead, the pump would increase its pressure as the flow decreases and then make the problem even worse.

One advantage of using a flow control system is that the water going thru a heater gets a high temperature drop and thereby gets a lower return temperate which is very good in a lot of places. This is good especially in heating systems using district heating.

The experimental study that was done compared a controlled and an unregulated pump. The controlled pump could run at three different settings; increasing the pressure as the flow increases, decreases the pressure as the flow increases and to keep the differential pressure constant as the flow changes. The pump had a very good way of creating the "right" differential pressure as the flow changes. In other words; it was worked very good and exact in creating the required pressure increase. The controlled pump had also a big energy saving potential compared to the unregulated pump if it is used in the right way.

6.2   Analysis

There are two ways of constructing flow control; with and without valves. It sounds like it is not the best way to build up a big pressure with the pump and then just remove a big part of it with the valves. That sounds like a waste of pump energy, and that it would be better to use just the pumps instead. On the other hand, the circuit using only pumps might be harder to control and might require more equipment. A circuit that is difficult to control is not such a good idea in a heating system.

One could argue if there is absolutely necessary to use flow control instead of a constant flow system in a heating system. On one hand, there is a big potential to save a lot of energy for the pump. On the other hand, the energy for powering the pump will transfer into heat that later can heat up the water that heats up the building. It is an ineffective way of heating but the energy comes to use. It is easier to understand its potential when there is a cooling system, and the heat from the pump is contra productive. For a heating system there is not so much to gain compared to a cooling system, when a flow control system is used.

One could see that the latest pump generation is much adopted to meet the demands from a flow control system. It is a very good idea to automatically change the speed of the pump. It is then possible to lower the energy consumption of the pump. It is also good that the pump can be programmed to get any pressure rise that is desired as the flow changes. This is as mentioned before that the pressure drop increases as the flow increases.

When a constant flow system is used, the pump is chosen to run at it most efficient speed at all time. The pump in a variable flow system sometimes needs run at speeds with bad efficiency. It therefore needs to be checked that the energy consumption is not higher because of lower efficiencies of the pumps. In the experimental study, the energy consumption was lower in spite of lower efficiencies of the pump so it could be a very good idea to use it.

As mentioned before, when there is a small flow in a system; a big part of the heat will be lost when going thru the pipes. It is therefore a risk by using the flow control system. This is because that when the heat demand for the heaters furthest away from the heat exchanger/boiler is small, a big percentage of the heat might be lost when going thru the pipes. It is therefore a risk that the heaters furthest away might not get the heat they require at some times if there is a flow control system. To prevent this it is important that the pipes are well insulated.

An advantage with the constant flow system is that it is easier to control than a flow control system. In a constant flow system, the heat output can be changed with just the temperature of the water. For a variable flow system, there are more factors that affects the is heat output. For the variable flow system both the temperature and the flow is affecting the heat output. The valve authority also risks getting reduced as the flow reduces.

6.3   Conclusions on the case study of using flow control

The energy savings for using the controlled pump instead of the unregulated is in some cases quite large and the biggest difference is when the flow is small. The controlled pump then uses much lower energy than when it is running for its highest flows. The reason why the controlled pump is using much less energy for the lower flows is because the pump then can lower its speed and thereby lowering its energy consumption. Even thou the pump has a lower efficiency at low flows the energy consumption is still lower.

Some points deviate from the normal lines. There are a lot of reasons why some points can deviate from the normal. The measurement equipment, for example is not 100 % reliable. Since it is an analog equipment, it could some times change get stuck when the measurement points are closely together. Then it is also some fluctuation in the system that makes it hard to get an exact value. There might also be some air inside the rig that is reducing the capacity of the pumps and the values might be misread.

6.4   Recommendation for further studies

In this project, the only component that has been more deeply analyzed is the pump. All the components have importance on the function of a flow control system. Therefore; it would be of great importance to have a good knowledge on what the problems are and what the possibilities are on using the other components in a flow control system. Since there is a limit of time in this project, the other components have not been as deeply analyzed as the pump has been. In further studies, it could be possible to analyze them as well.

No complex calculations have been carried out in this project. It was the intension of this project to calculate on the whether the examples in Chapter 5 could function even if the systems were change. Due to lack of information and time, it was not possible to do this. In future studies it could be an idea to do calculations on flow control systems to see how good they can function.

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Appendix 1

District heating

This appendix contains the general demands are on the design of the secondary side on the district heating system, demanded from "Svensk Fjärrvärme AB". The information is from their documentation of what demands they require for building district heating system on the secondary side.

Demands from "Svensk Fjärrvärme AB"

In the design of the district heating system on the secondary side it is important to get a low return temperature to the primary side. Therefore it requires an effective heat exchanger. An effective heat exchanger has a difference between the primary- and the secondary's return temperature of about 3 degrees Celsius [10].

Since the Swedish National Board of Housing, Building and Planning, "Boverket", demands at least 50 degrees Celsius water in a water system, the water from the secondary side is recommended to be 55 °C. If an accumulator tank is included in the design, the hot water needs to be heated up to 60 °C [10].

The return temperatures should be kept as low as possible. "Svensk Fjärrvärme AB" has made a table of the demand for return temperatures at the dimensioning outside temperatures for the specific locations [10]:

High-/low pressure systems	District heating Supply	District heating Return	Radiator systems supply temperature	Radiator systems return temperature
Heating systems in new buildings	100/80 °C	<48 °C	60 °C	45 °C
		<43 °C	60 °C	40 °C
		<33 °C	70 °C	30 °C
Ventilation systems in new buildings	100/80 °C	<33 °C	60 °C	30 °C
Heating system in older buildings	100/80 °C	<63 °C	80 °C	60 °C
After improvements	100/80 °C	53 °C	70 °C	50 °C

Appendix 2

Here is the Matlab codes used for plotting the maximal systematic error in the example in Chapter 2.4.

```matlab
clear all
close all
clc

M=linspace(0,2);

t1=80;
dt=2; %3
t2=40;
cp=4.2;
for i=1:length(M)
    dM=0.05*M(i); %=0.1*M(i);
    Q(i)=M(i)*cp*(t1-t2);
    deltaQ(i)=Q(i)+cp*(((t1-t2)*dM)+(M(i)*dt));
    deltaQ2(i)=Q(i)+cp*(((t1-t2)*-dM)+(M(i)*-dt));

end
hold on
plot(M, Q)
plot(M, deltaQ, 'r')
plot(M, deltaQ2, 'r')
```

Appendix 3

Below one could see the different steeps on how the experiment should be carried out and a description on how the rig should be set up.

The following steps should be conducted in order to set up the rig:

1; Fill the yellow container with water by unscrewing the handle. Then screw the handle back.
2; Connect the hose on the container to the rig at the position on the left side at the bottom.
3; Pump water into the rig from the yellow container.
4; Screw on the five air valves in order to let out air inside the rig. Then close the two air valves in the middle (the two connected to the same container), See the circles on the figure below.
5; Continue to pump water until the rig has a pressure of 1 bar which is the standard pressure level for heating systems less than 10 m high.

The following steps should be done for the first part:

(See the picture above for the names of the different components)

1; Open the valve (e) after the unregulated pump (the left one) and open the valve (h) at the top of the rig
2; Turn the setting on the pump to its first position
3; Open valve (i) to its maximum
4; Measure the Energy usage (a), differential pressure (b) and the water flow (c)
5; Set valve (i) to a new position in order to increase the pressure loss in the system
6; Measure the new Energy usage (a), differential pressure (b) and the water flow (c)
7; Continue to close (i) valve and measure the three parameters until the valve is fully closed
8; Turn the setting of the pump to its second position and redo number 3-7
9; Turn the setting of the pump to its third position and redo number 3-7

Task: Find the operational points for the rig and plot the pump curves.

The following steps should be done for the second part:

 (See the picture above for the names of the different components)

1; Open the valve (f) after the controlled pump (the right one) and open the valve (h) at the top of the rig
2; Turn the setting on the pump to its first position
3; Open valve (i) to its maximum
4; Measure the Energy usage (a), differential pressure (b) and the water flow (c)
5; Set valve (i) to a new position in order to increase the pressure loss in the system
6; Measure the new Energy usage (a), differential pressure (b) and the water flow (c)
7; Continue to close valve (i) and measure the three parameters until the valve is fully closed
8; Turn the setting of the pump to its second position and redo number 3-7
9; Turn the setting of the pump to its third position and redo number 3-7

Task: Plot the operational points for the rig. Analyze how the different settings work.

Appendix 4

Measured values from the Practical example

Here are the measured values in the laboratory exercise

For the first speed of the unregulated pump:

Flow [l/h]	Pressure difference [Bar]	Pump Drive Power [W]
560	5,2	36,5
500	6,1	36,7
450	6,2	36,4
400	6,4	36,3
350	6,8	36,4
300	7,1	36,3
250	7,4	36,2
200	7,8	36,1
100	8,3	35,9
0	8,8	35,6

For the second speed of the unregulated pump:

Flow [l/h]	Pressure difference [Bar]	Pump Drive Power [W]
800	9,8	49,8
750	10	49,6
700	10,3	51
650	10,7	50,4
600	10,9	50,2
550	11,2	50,1
500	12,3	50
450	13	49,9

400	13,3	49,6
300	14,8	49,2
200	16,8	48,4
100	18,2	47,9

For the third speed of the unregulated pump:

Flow [l/h]	Pressure difference [Bar]	Pump Drive Power [W]
1000	14,9	58,2
900	15,9	58,1
800	16,8	57,8
700	20,9	57
600	22,2	56,4
500	24,1	56
400	25,8	55,5
300	27,5	55
200	29	54,4
100	30,5	53,7
0	31,5	53,5

For setting 1 of the controlled pump:

Flow [l/h]	Pressure difference [Bar]	Pump Drive Power [W]
810	9,3	15,4
750	9,8	15,3
700	10	15,2
650	10,3	15
600	10,5	14,5
550	10,8	14,2

500	11,2	14
400	11,7	13,4
300	11,8	12,6
200	11,8	11,4
100	11,6	10,5
0	11,6	9,5

For setting 3 of the controlled pump:

Flow [l/h]	Pressure difference [Bar]	Pump Drive Power [W]
1250	19,8	52,4
1200	20,7	52
1100	22,2	52,8
1000	24,1	53,9
900	26	57
800	27,1	53,8
700	27,8	51,1
600	27,3	47,5
500	27,1	41,5
400	26,8	38,6
300	26,8	35,8
200	25,8	31,5
100	24,5	29
0	24	26,6

For setting 5 of the controlled pump:

Flow [l/h]	Pressure difference [Bar]	Pump Drive Power [W]
1250	19,2	51,3

1200	21,8	51,5
1100	22,1	52,8
1000	24,1	54,5
900	26,7	56
800	28,9	58,3
700	31,8	58,8
600	32,4	58,2
500	33,8	57,7
400	35,1	57
300	36,1	56
200	38,4	54,7
100	38	54
0	38,8	53