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AKUREYRI'S DISTRICT HEATING SYSTEM: AN OPTIMIZATION STUDY

Optimization of supply temperature

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A 30 credit units Master´s thesis

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A Master's thesis done at
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ABSTRACT

Iceland is in first place in the world for direct use of geothermal energy per capita. The largest use of low temperature geothermal energy is for space heating in large districts of towns. The water sent to consumers in Akureyri town in north Iceland is a mix of hot geothermal water and water returning from users' radiators. The goal of this work is to optimize the supply temperature to the district heating distribution network, in order to minimize the amount of water extracted from geothermal fields.

First the district heating system in Akureyri is described. Information on utilized geothermal fields, distribution system and equipment such as pumps, storage tanks, pipelines, etc. is presented. It is explained how the system is controlled.

The second part is a case study. Operational optimization of Naustahverfi's district heating system is performed. A running curve for supply water temperature at the pumping station is designed and a mathematical model for this optimization is used. The choice is a macroscopic model that lumps the system into one equivalent user. Data on the supply water temperature and flow as well as outdoor temperature, provided by Norðurorka Company, is used for the simulation. A curve representing the lowest geothermal water consumption is found. The work reveals and addresses the limitations of a macroscopic model. It shows how the problem can be solved in case of unsuitability of part of the data and points out the need to modify the existing theory to include snow melting installations.

PREFACE

This work was done as a part of RES's MSc Program in Renewable Energy Science in Akureyri, Iceland.
The geothermal district heating system in Akureyri is operated by Norðurorka. The company enabled me to work on a real system to optimize the supply temperature in the pumping station. The work has two main parts. In first I described the district heating system, in the second I found the optimum supply temperature regulation for the distribution system in Naustahverfi district. The particular district was chosen because of the availability of measurements.
The district heating system in Akureyri is complicated and had to be well described. In this part of work I used information from the engineers working at Norðurorka. In the second part, a mathematical model was built and simulations were run. Initially the solution was supposed to be obtained through a microscopic model describing design details of the system. The model was based on General Network Analysis Theory. This idea had to be abandoned due to the number of assumptions necessary to build the model. Finally a macroscopic model was chosen. Data on supply, return, outdoor temperatures and water flow at the pumping station was used. During modeling it turned out that a return water temperature data cannot be used since the model theory does not take into account the cooling of return water in snow melting installations. The return water temperature data had to be ignored and assumptions about reference parameters were made. The model was built and simulations run. The result was a running curve assuring the lowest consumption of geothermal water.
The work reveals and addresses the limitations of the macroscopic district heating model used.

I would like to thank my advisors, Stefán H. Steindórsson and Páll Valdimarsson for guiding me through the work.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

The role of a district heating system is to maintain indoor temperature at a certain, relatively constant level and also to provide hot tap water. The system has to deliver heat to the building to counter for heat losses to the surroundings and provide the tap water at sufficient temperature and pressure. (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993) From the view point of consumers, a district heating system has to satisfy their needs at the lowest possible price. From the view point of a provider – a district heating company – the system should work in such a way that the energy is delivered to the consumers at the lowest costs, thus maximizing the company's benefit.
This means that both the district heating company and consumers are interested in low costs of energy provision.

Hydrothermal geothermal district heating systems use hot rock and ground water extracted from depths of a few hundreds to even a few thousands of meters (3000 meters is an economical limit for commercial utilization). The temperature of the fluid is rather low (70 – 90 °C). (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993) If extracted water has good chemical properties (extensive scaling and corrosion does not occur) it can be transported directly to consumers through the district heating network. After cooling down at consumers' radiators the temperature drops to around 30 – 40 °C. This makes reheating of return water impossible. (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993)

Opposite of fossil fuelled district heating systems, the temperature of hot water produced in a geothermal district heating system cannot be controlled. Extracted fluid has to be mixed with colder water to adjust the temperature of water supplied to buildings. A common practice is to dispose or re-inject a part of the return water – coming from radiators - and mix the rest with hot water coming from wells. The temperature of water in a district heating network can be adjusted by mixing in a three-way valve.
The optimum level of this temperature is different for each district heating system and depends on:

- the design – sizes of pipes affect pumping cost
- technical structure (dependent on geographical and urban conditions) – pipe lengths affect heat losses
- line heat demand – heat demand per one meter of pipe
- cost structure – cost of electricity for pumping (Bøhm & Larsen, 2004)

The purpose of operational optimization of district heating is fine tuning of the system. This means that none or small modifications (control equipment) are applied to existing facilities. The role of operational regulation is to control provision of the heat in order to maintain adequate temperature in the buildings connected to the system at each moment.
Since indoor temperature can be assumed constant, the heat demand will depend on weather conditions and consumer behavior. Weather factors like hours of sunshine per day, cloud coverage and wind speed are of relatively small importance and the influence of weather on the operation of a district heating system is mainly through the outdoor

temperature (Valdimarsson, 1993). This means that district heating system operation can be adjusted by changing the heating water temperature and flow with respect to outdoor temperature.

It is easy to explain why the efficiency of fossil fueled systems is of very big importance – the less efficient the system, the more fuel has to be used and the higher the costs are. In the case of geothermal, efficiency is also important.
In general the cost of a district heating system can be divided into capital cost and operational costs. Capital cost is the cost of investments that have to be made before the system begins to operate and is the highest of all costs for geothermal district heating.
First geological exploration has to be carried out, including exploratory drilling. Then production and sometimes injection wells have to be drilled and well pumps have to be installed. Finally the district heating system has to be designed and built.
Operational costs in geothermal district heating system are pumping costs and system maintenance costs and are small compared to capital cost, which is opposite to fossil fueled systems, where the cost of fuel is the major cost.
Geothermal energy is a renewable source, but it has some limits. If it is exploited on a large scale it cannot be treated as inexhaustible. During utilization, the water level in the reservoir drops. This phenomenon is called drawdown. Pressure and temperature also decrease. The rates of changes vary and they are different for each geothermal field. The effect is that it becomes less economical to extract the energy from a particular place. New wells have to be drilled and this means a lot of money has to be invested - exploration and drilling is very expensive. The more efficient the system, the less fluid is pumped from fields and the longer the existing wells will be sufficient for supply.
Although operational costs are small compared to investments, they still have a significant share in the total cost of geothermal district heating system. These are mainly pumping (electricity) costs. Geothermal water has to be pumped to the surface from a well and very often transported over long distance to the town. The bigger the flow the bigger the electricity consumption is. What is more, high flow from the field causes large drawdown which makes pumping inefficient. Apart from pumps required for hot water transportation from fields to the system, there are also pumps that maintain water circulation within the town, but the electricity cost for their operation is relatively small and can often be neglected in system optimization (Steindórsson, 2009).

To recapitulate, the system should be optimized in such a way that the amount of extracted and transported water from fields used to satisfy the needs of consumers is minimal. Since the main factor influencing system operation is outdoor temperature, the mixing temperature and flow should be adjusted with respect to outdoor temperature and this can be done with a thermostatic three-way mixing valve and frequency regulated pump that responds to changes in demand. A relation between the outside temperature and optimal supply temperature has to be found. In other worlds a running curve has to be created. Such curves are popular in heating regulation applications and in most cases are derived empirically. District heating systems are complicated networks and their behavior, when subjected to different conditions, is difficult to predict. This is when computer methods are useful. To design a controller relating outdoor temperature with mixing temperature, a mathematical model has to be built and computer simulations have to be made.

A macroscopic model is a model that lumps all users into one equivalent and data from the pumping station is used. Design details of the system, like pipe dimensions and coordinates, don’t have to be studied. Data cannot be used directly and some preparation is required, i.e. to separate tap and radiator water. Data suitability should also be examined. Installations like snow melting, which are gaining popularity in Nordic countries like Iceland, can greatly influence the return temperature profile. In such situations a macroscopic model that does not take into account such installations will fail if return data is used straight away.

2 GEOTHERMAL HEATING IN AKUREYRI

2.1 Akureyri and its climate

Akureyri is a town located in north-central Iceland. It is the second largest urban area after the Greater Reykjavík area but is the fourth largest municipality in Iceland after Hafnarfjörður, Kópavogur and Reykjavík. As of the 1 April 2008 census, the town had a total population of 17,304 (Hagstofa Íslands, 2008).
It is an important fishing, trading, industry, services, educational and transport centre. The second Icelandic university is situated here.

Fig. 2.1 Akureyri in Iceland

Akureyri is located at 65°41′N 18°06′W and positioned on the west side of the inland end of the Eyja fjord. It is surrounded by mountains, the highest being Súlur 1213 m and Hlíðarfjall 1116 m.

The climate here can be classified as sub-polar oceanic and is considerably a milder climate than its location just south of the Arctic Circle would imply. The North Atlantic Current ensures that the winters are mild and windy while the summers are damp and cool. Because of Akureyri's position at the end of a long fjord surrounded by high mountains, the climate is actually more inland than coastal, meaning greater variations in temperature (warmer summers, colder winters) than in many other inhabited parts of Iceland. The surrounding mountains also shield the town from strong winds.
The annual mean temperature on the northern coastline is lower than along the coasts of southern and southwestern Iceland and is below 4 °C. The average temperature of the warmest months (June, July and August) exceeds 10 °C. The warmest summer days around Iceland can reach 20-25 °C. In the coldest months (December, January and February) the average temperature is above -3 °C (Lamb, 1995) (Veðurstofa Íslands, 2008).

2.2 History of geothermal district heating system in Akureyri

Akureyri has been heated by geothermal energy since the end of the seventies. Prior to that, it was mainly heated with oil burners, located within individual buildings. Before the geothermal heating system was built, many users switched to electrical heating. The oil crisis of 1973 caused a jump in energy prices. Considerable effort was put into geological exploration. Laugaland field was selected for deep drilling. In 1975 a big feed zone was discovered, which initially yielded around 100 l/s of 90 °C hot water by free flow. Two years later another big feed zone was located at the Ytri-Tjarnir geothermal field initially yielding 50 l/s of 80 °C water. It was estimated that these two fields together could yield 240 l/s with a water level drawdown to 190 m below the surface. This was expected to satisfy the energy need for space heating in Akureyri. In 1977, Hitaveita Akureyrar (Akureyri District Heating) was established. Construction of the district heating system was initiated in 1976. The first house was connected in late 1977 and most of the town was connected in 1979 (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

Hitaveita Akureyrar was the first big district heating system in north Iceland. Earlier only a small one existed in Olafsfjörður, which utilized a small part of its capacity using free flow. That is why empirical data from fields in SW Iceland had to be used when the performance of fields was predicted, although reservoirs in north Iceland are much more of a closed type than those in the Rejkjavik area. Soon after pumping from the fields began it became evident that the drawdown would be much greater. Since pump design limited the drawdown to 240 m at Laugaland and 330 m at Ytri-Tjarnir, the average annual production declined rapidly with time. After a few years in operation, the annual average production from these fields was reduced to 75 l/s. This unforeseen decline was answered by an almost desperate exploration for more geothermal water, mainly by drilling. This resulted in many wells that are now inutile. Later the approach changed. Careful surface exploration started and was followed by successful drilling. This resulted in the discovery of productive feed zones at three different geothermal fields: Botn in 1980, Glerárdalur in 1981 and Þelamörk in 1992 (Flovenz, Ártnason, Finnsson, & Axelsson, 2000) (Steindórsson, 2009).

In 1999 geothermal prospecting in the vicinity of Hjalteyri was initiated. It turned out that the Hjalteyri low temperature area is among the most productive in Iceland, capable of yielding around 200 L/s of 90 °C hot water at moderate drawdown rates over extended periods of time. Hjalteyri was connected to the system in December 2003. (Gautason, o.fl., 2005)

2.3 District heating system in Akureyri – design and operation

2.3.1 Geothermal utilization in Akureyri

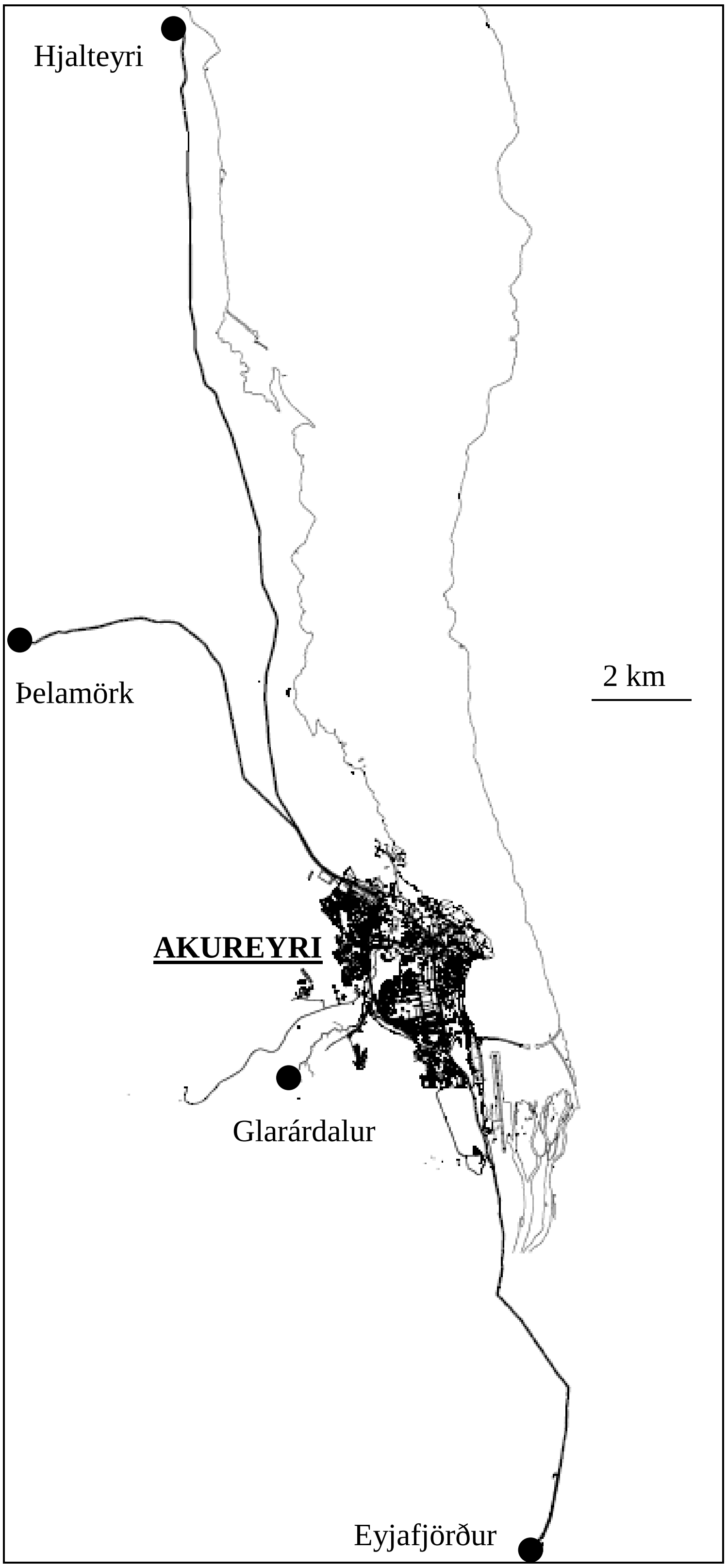

Fig. 2.2 Akureyri and its fields

Hot water is pumped from four different locations towards Akureyri: from the Eyjafjördur geothermal fields, 12-14 km south of the town; from Glerárdalur, 2 km west of the town; from Þelamörk, 10 km north of the town and from Hjalteyri, 19 km north of the town (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

In Eyjafjördur, Þelamörk and Hjalteyri a part of the hot water is used for local consumption, but the main part is pumped to Akureyri. Water from Glerárdalur is pumped directly from the boreholes to Akureyri. There are pump stations at Þelamörk and Hjalteyri. Water from Eyjafjördur fields is first collected at the Laugaland Pumping Station (LPS) from which it is pumped along the transmission pipe to Akureyri (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

Because of elevation differences within the town, the distribution system is divided into two separate parts: the upper (high pressure) and lower (low pressure) distribution systems. Each part has its own storage tank. The lower tank is situated in the southern part of town, at the Central Pumping Station (CPS). The upper tank is in the western part of town. The purpose of the tanks is to filter out short-term changes in consumption and to have some reserve water available at all times in case of a system failure (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

At the Akureyri Central Pumping Station the water from Eyjafjördur and Glerárdalur fields, as well as a part of the return water, is blended in a lower storage tank before it is pumped to customers (Steindórsson, 2009).

From the CPS the water goes to the low pressure part of the district heating system (lower tank) and sometimes to the high pressure zone if needed.

Water from Hjalteyri and Þelamörk fields is pumped to Sjöfn Pumping Station situated in the northern part of town where it is mixed with return water. It supplies the high pressure part of the system and the upper tank but can also flow into the low pressure zone (Árnason, 2009).

The total length of the pipelines in the distribution network in Akureyri is 469 km (Norðurorka, 2009).

The temperature of water from boreholes is between 60 °C and 103 °C. The temperature of water reaching consumers is in the range of 60-80 °C, but in extreme cases it may fall below 45 °C during hot summer days due to long cooling time in pipelines. The return water has a temperature of approx. 27 °C (Steindórsson, 2009).

Geothermal water is utilized both for heating and tap water. Of the total consumption, 87% is for space heating, but 13% is for bathing, washing and other purposes (Norðurorka, 2009).

Since the water from the fields has low mineral content and extensive corrosion or scaling does not occur, there is no need for heat exchangers between the boreholes and the consumers. Only a small number of users have heat exchangers for tap water installed.

About 20% of hot water that is sent to the consumers is recollected, especially from those parts of Akureyri with the highest population density. In general those are big buildings. Return water from the district heating system is mixed with supply water to regulate the temperature or is re-injected in Laugaland field. In many buildings, water returning from radiators is used for snow melting before flowing into the return network. The portion of return water that is not recollected is disposed through a sewage system to the fjord.

Hrisey Island, which belongs to Akureyri, is also heated with geothermal energy but has a separate artesian well and is not connected to the town system (Steindórsson, 2009).

2.3.2 Norðurorka

Nordurorka was established August 1st, 2000 with the merger of the Akureyri Electricity Utility (1922) and the Akureyri Heating (1977) and Water Utilities (1914) and provides Akureyri with heating, electricity and water.

The main business of the company is:

- Supplying, distributing and selling of thermal energy
- Supplying, distributing and selling of water
- Distributing electric energy

As for the heating, Norðurorka is responsible for hot water extraction, transportation towards the city and distribution to the consumers and maintenance of those installations. Installations in buildings are excluded from company‘s supervision but must conform to standards (Steindórsson, 2009).

2.3.3 Fields

Eyjafjörður

Eyjafjördur geothermal fields are a combination of three separate geothermal fields: Laugaland, Ytri-Tjarnir and Botn. Together six boreholes are utilized here for hot water production (Steindórsson, 2009).

A part of the hot water is used for local consumption (Hrafnagil community is connected directly to Botn Field), but the main part of the water from Eyjafjördur fields is pumped to Akureyri. It is first collected at the Laugaland Pumping Station (LPS) where it passes through a degasser, which is a 300 m3 insulated storage tank, before being pumped towards Akureyri by two Floway 14FKH pumps. They have six stages each, 224 kW motors and rotational speed of 1450 rpm. Their performance is 170 l/s. Under normal load, only one of the pumps is used – the second serves as a peak and reserve pump. During the winter time electrical system failure may occur, especially in bad weather when snow and ice break the electrical power lines. To account for this, a 1500-kVA power station has been installed at the LPS. Therefore, the pumping from the Eyjafjördur fields towards Akureyri is not dependent on external electrical power (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

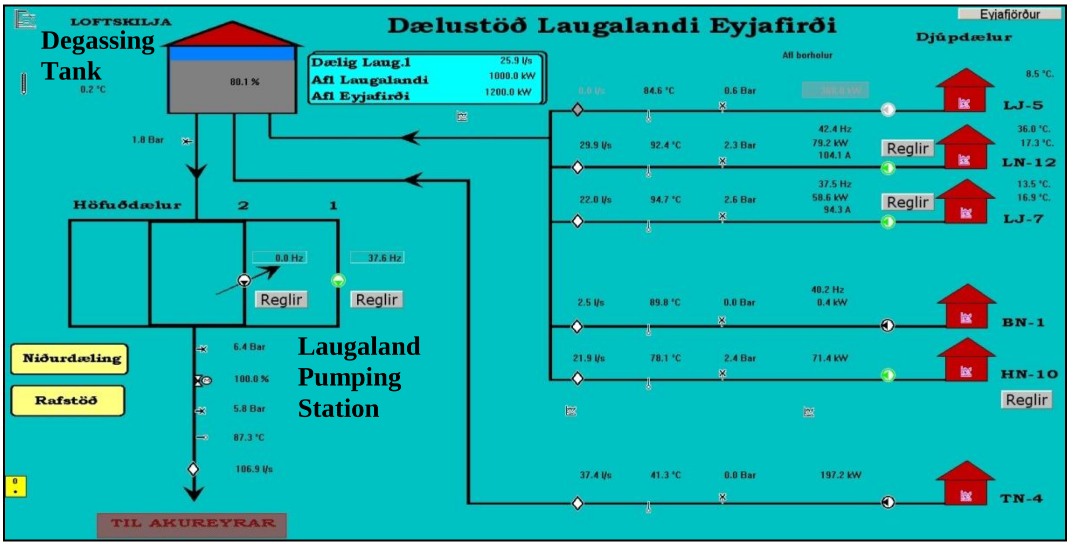

Fig. 2.3 Collection of geothermal water at Eyjafjörður (Scada)

At Laugaland three boreholes can be used for production: LJ-5 and LN-12 yield 40 l/s each and LJ-7 yields 62 l/s maximum flow. Three Floway rotary-shaft down-hole pumps are installed. At LJ-5 and LN-12 184 kW and at LJ-7 220 kW motors drive the pumps. The pumps at LN-12 and LJ-7 have regulated rotational speed (Norðurorka, 2009).

At Botn two boreholes are in use: BN-1 and HN-10 yield 4 and 26 l/s maximum flow respectively. BN-1 has a frequency regulated Goulds down-hole pump installed with an 11 kW submersible motor. At HN-10, a Floway rotary-shaft pump with a 184 kW motor is running. The Floway pump has regulated rotational speed (Norðurorka, 2009).

Ytri-Tjarnir‘s TN-4 borehole is equiped with a Reda down-hole pump submersible motor, which runns at 200 kW, only in wintertime, with an average flow of 34 l/s (Norðurorka, 2009).

Water from all three fields is collected in one degassing tank before going to the pumping station. To eliminate oxygen from the water, sodium sulfide is added. A small amount of water going from Laugaland pumping station towards Akureyri is taken to a small tank. Sodium sulfide is mixed into the water there. The water is then mixed into the pipe connecting the TN-4 borehole to the degassing tank.
From the LPS the water is pumped along the transmission pipe to Akureyri CPS. The temperature of water depends on which fields are in use and is around 87 °C.
A part of the return water recollected in Akureyri is transported back to Laugaland field and re-injected there. Two boreholes are used for re-injection:LJ-8 and LJ-10. Re-injection is very beneficial, especially in this region because of the closed nature of reservoirs here, which experience high drawdown. (Árnason, 2009)

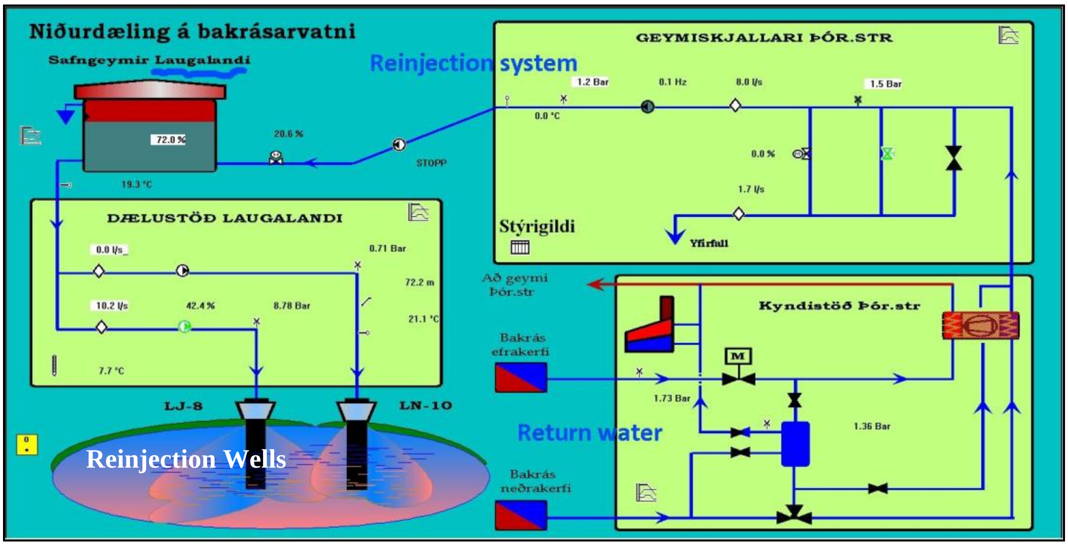

Fig. 2.4 Reinjection at Laugaland (Scada)

Glerárdalur

Glerárdalur is the coldest field utilized by Hitaveita Akureyrar (Akureyri District Heating). It is utilized only in wintertime. One well is in use and the geothermal field provides water at temperature of only 60 °C which during most of the year is below the system's temperature. Since Glerárdalur is located just 2 km outside Akureyri, and at an elevation of 220 m, the water is pumped directly from the borehole through a small degassing tank and to the CPS at Akureyri (Flovenz, Ártnason, Finnsson, & Axelsson, 2000) (Árnason, 2009).

The temperature is too low to use the water directly and it can be heated up with 6-MW electric boiler at a 'MS' dairy farm situated close to the field in Súluvegur, but this is done very rarely due to electricity costs. That is why from the tank the water goes to the CPS, where it is mixed with warmer water coming from Eyjafjörður before entering the lower pressure tank. (Árnason, 2009)

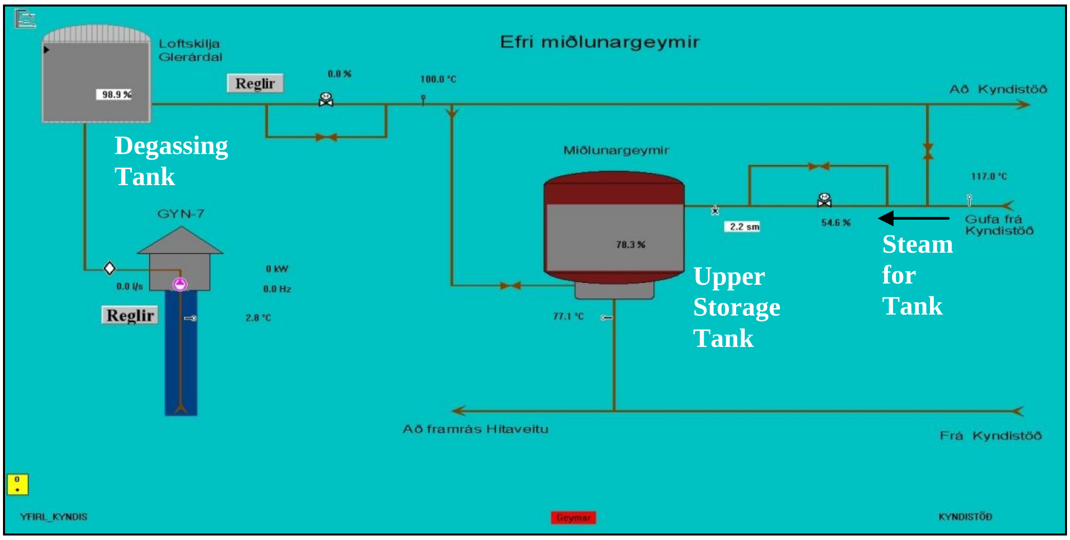

Fig. 2.5 Extraction at Glerárdalur (Scada)

The GYN-7 borehole is equipped with a Goulds downhole pump, which has 75 kW submersible motor. The maximum flow from the field is 20 l/s. The pump's rotational speed can be regulated (Norðurorka, 2009).

Hjalteyri

Hjalteyri geothermal field yields more than 100 l/s of ~87 °C water. It is the most economical area fromwhich to pump water. It consumes just a little more electricity than Ytri-Tjarnir, which provides 35 - 40 l/s of 86 °C water and is the least economical geothermal field (Steindórsson, 2009).
Hjalteyri is also the most productive field supplying Akureyri's district heating system - Hjalteyri's two boreholes (HJ-19, HJ-20) are about an order of magnitude more productive than other geothermal systems utilized by Hitaveita Akureyrar. The number of new users serviced by the Hjalteyri field is relatively small. However, the field provides much needed relief for the heavily exploited fields south of Akureyri (Gautason, o.fl., 2005). Hjalteyri serves for base load all year round since it has very small drawdown compared to the rest of the fields. A small portion of the water is used for local users. The rest is pumped in two directions – Sjöfn substation and Þelamörk. From the pumping station at Hjalteyri water, at around 87 °C, is pumped 19 kilometers to Sjöfn. Supply and return waters are mixed there and the water flows further to the upper Akureyri district heating system. Water pumped in the direction of Þelamörk supplies Arnareshreppur. The flow is around 3 l/s and the connection was made according to an agreement reached when Hjalteyri field was established, to provide 15 farms with hot water (Steindórsson, 2009).
Since the consumption of the community is small and the furthermost user is located at a large distance from the field, a relatively significant amount of water has to be pumped. This water is pumped further to Þelamörk field (Árnason, 2009).

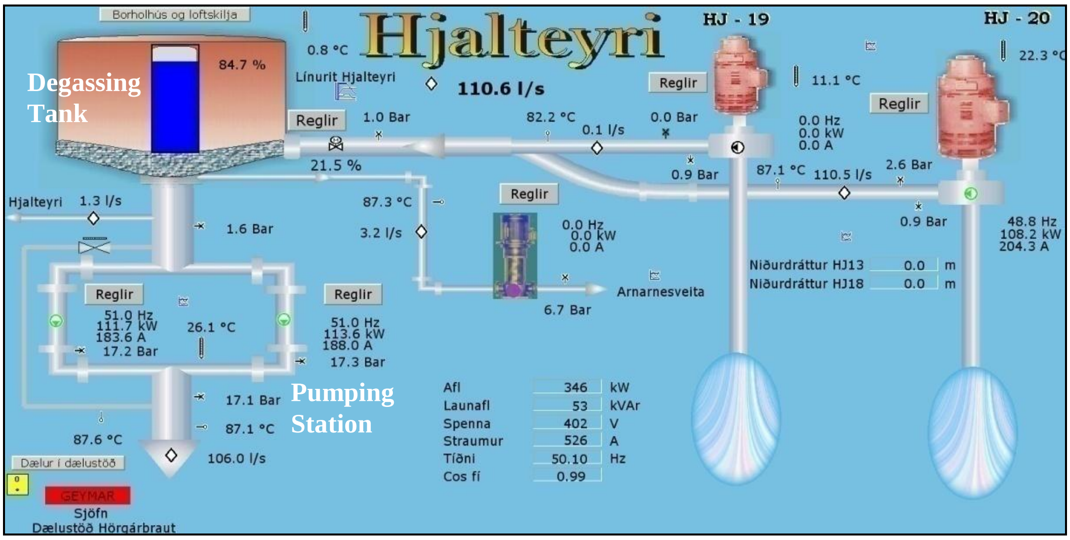

Fig. 2.6 Extraction at Hjalteyri (Scada)

At Hjalteyri geothermal field two boreholes can be used for production: HJ-19 yielding 80 l/s and HJ-20 yielding 120 l/s maximum flow. Two Floway frequency-regulated rotary-shaft downhole pumps are installed with 112.5 and 150 kW motors respectively. (Norðurorka, 2009)

The water from the boreholes goes to a degassing tank. The portion of water supplying Akureyri flows to a nearby pumping station in a DN400 insulated pipe. At the station two pumps are operating. To maintain 110 l/s flow towards Akureyri around 17 bar pressure at the pump station is required from which 5 bar are only to overcome the level difference between Hjalteyri and upper tank in the town (around 50 meters). From the two boreholes, HJ-20 is used in most cases for production because maximum flow to the town is limited (an additional pump on the way to Akureyri would have to be added to increase it) (Árnason, 2009).

Þelamörk

Þelamörk is currently the hottest field supplying the district heating system. Two boreholes can be used for production. Since successful deepening of the well LÞN-10 towards the main fracture zone in the year 2000, it yields water at temperature 102°-103 °C (after deepening the borehole was renamed LÞNS-10) (Hjartarson, Axelsson, & Steinunn, 2002) (Steindórsson, 2009).
88°-93 °C water from Þelamörk is pumped 10 kilometers by four pumps towards Sjöfn in the north part of Akureyri. The outlet temperature from the pumping station is around 90 °C. To maintain 30 l/s flow towards Akureyri around 14 bar pressure at the pump station is required. On the way to town the pipeline supplies local consumers (Árnason, 2009).
In the warmest summer periods, when Akureyri's demand for hot water is low, Þelamörk is not in use. During that time a portion of the water from Hjalteyri is pumped to Þelamörk, supplying the local swimming pool and is then re-injected in LÞN-5 well. Water flows through the same Þelamörk-Sjöfn pipeline but in the opposite direction. Reinjection reduces the drawdown and thus Þelamörk can take peak loads in the winter (Steindórsson, 2009).

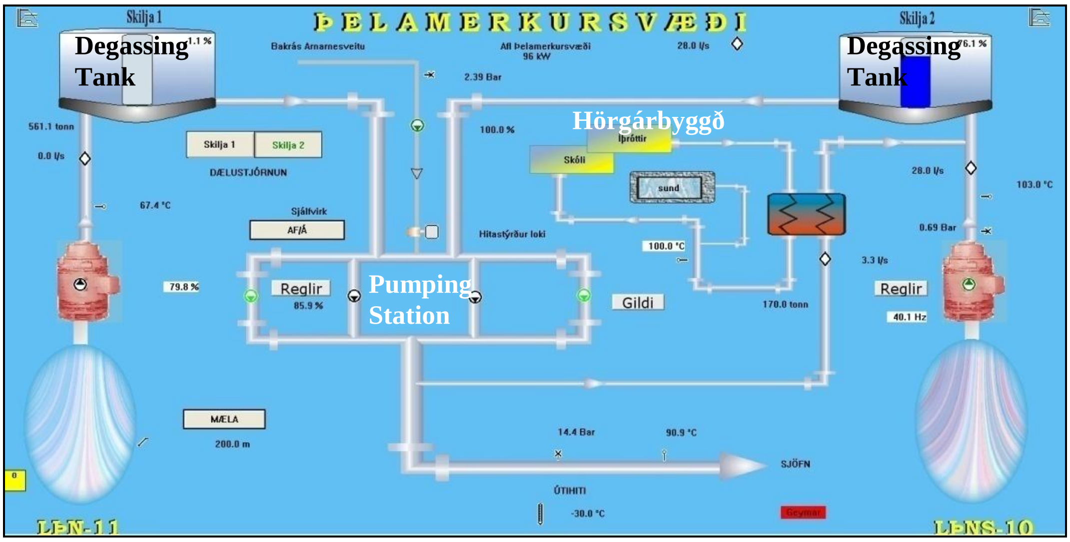

Fig. 2.7 Extraction at Þelamörk (Scada)

LÞN-11 yields 14,5 l/s and LÞNS-10 26 l/s maximum flow. Two Floway rotary-shaft downhole pumps are installed with 74 and 184 kW motors respectively. The pump at MÞNS-10 is frequency regulated. Water from each borehole goes to a separate, 20 m3 degassing tank (Norðurorka, 2009) (Árnason, 2009).

Currently only well LÞNS-10 is in operation and LÞN-11 is used only in case of failure. Water coming from LÞNS-10 has a temperature of 103 °C and has to be cooled down before entering the degassing tank. This is done by mixing with the 30-40 °C return water from the local swimming pool and school complex in Hörgárbyggð (Fig. 2.7). The pressure in the borehole has to be kept above 0.61 bar so that steam does not form in LÞNS-10. A valve on the pipe with water coming from the swimming pool was installed for this purpose (Fig. 2.7).

After leaving the degassing tanks water is mixed with colder (~86 °C) surplus supply water coming from Hjalteyri through Arnareshreppur community and enters nearby pumping station (Árnason, 2009).

In case of LÞNS-10 failure, 91 °C water from LÞN-10 borehole can be pumped but it cannot be blended with Arnareshreppur water anymore because the temperature after mixing would be too low for supplying the town. In this case Arnareshreppur water is re-injected into well LÞN-2 (Árnason, 2009).

2.3.4 Pipelines

The pipeline connecting Eyjafjörður fields with the Akureyri system is overground. Subsurface pipelines from Eyjafjörður, Þelamörk and Hjalteyri don‘t have any compensation devices. The thermal expansion is taken up by stresses in the buried pipeline. Bellow compensators are mounted only at pumping stations (Árnason, 2009).

Eyjafjörður

The transmision pipe from Eyjafjörður is of a different type than the pipelines connecting other fields to town. It is a 508-mm diameter steel pipe insulated with water resistant Rockwool and covered with a thin aluminum cover. Only about 1.3 km of the 12 km pipeline is buried in a concrete tunnel, while most of it rests on 1-2 m high concrete columns spaced 9 m apart. The pipeline can move freely on the concrete columns except at every tenth column where it is either a fixed point or an expansion unit to take up thermal expansion in the pipeline. The cooling in the 12-km pipeline is close to 2 °C for a flow of 100 l/s (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

Glerárdalur

Water from Glerárdalur is transported to the town in a buried DN150 pre-insulated pipeline without compensation (Norðurorka, 2009).

Hjalteyri

Water from Hjalteyri is transported in a buried pre-insulated pipeline. The diameter of the steel pipe is 300 mm and the diameter of the casing is 500 mm. These are Logstor pipes, insulation series I (Steindórsson, 2009).

Þelamörk

The transmission pipeline from Þelamörk to Akureyri consists of a 4.5-mm thick steel pipe, 193.7 mm in diameter and with 60-mm thick polyurethane insulation, covered with a polyethylene coat. The estimated temperature loss along the pipeline is 6 °C (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

2.4 Distribution system

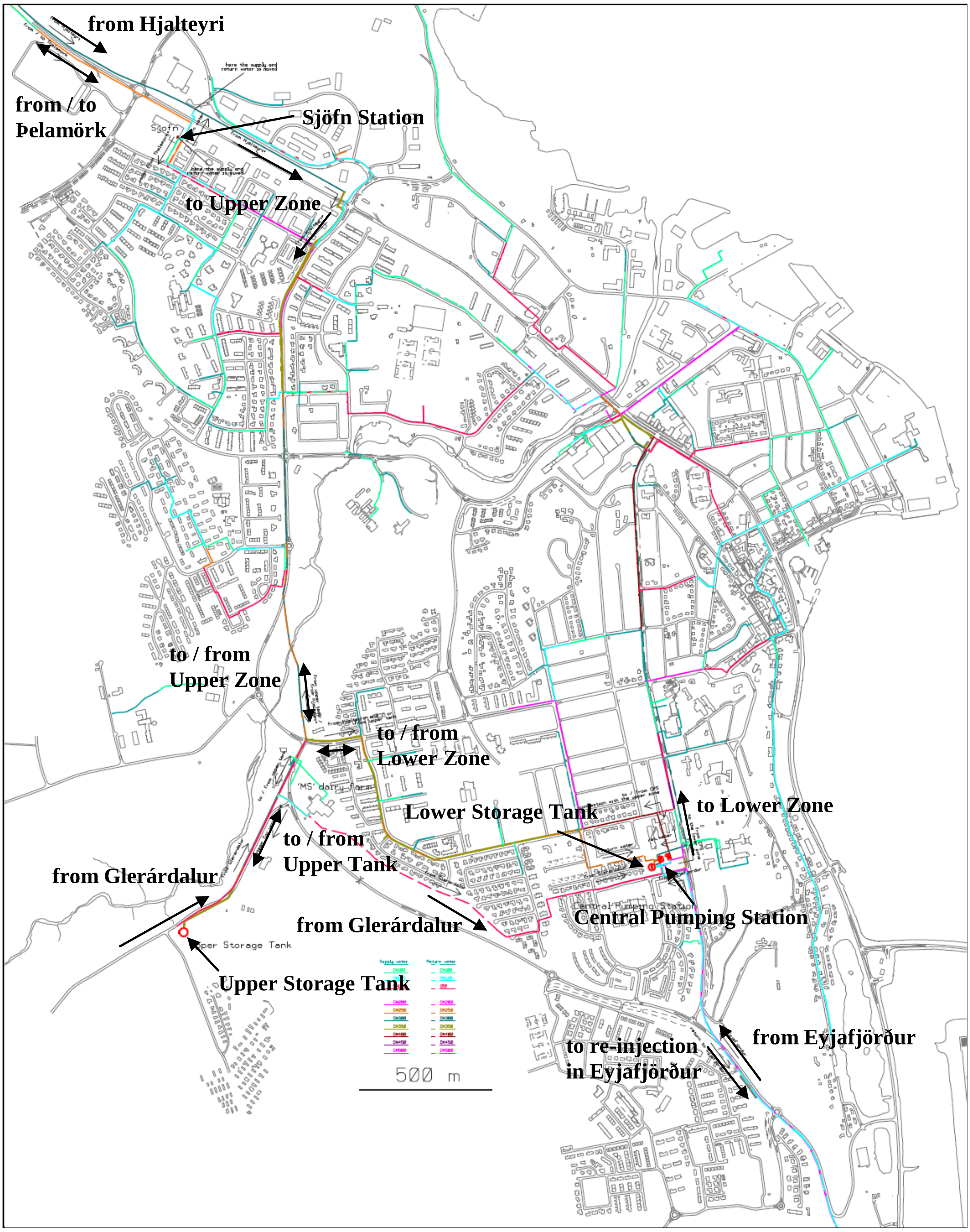

Fig. 2.8 Akureyri's heating distribution system

2.4.1 Central Pumping Station

A 2500 m3 storage tank, heat pumps, 1-MW electrical boiler and the oil burner are located at the CPS (Fig. 2.11).
87 °C water from Eyjafjörður is pumped to the CPS. It is mixed with ~27 °C return water from the town and ~60 °C water from Glerárdalur and flows to the tank. The tank is made of steel and insulated by Rockwool (Norðurorka, 2009).

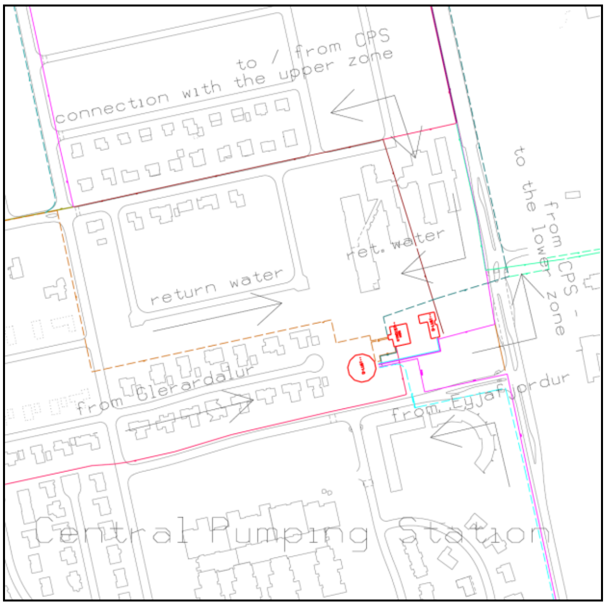

Fig. 2.9 Central Pumping Station

To limit the amount of water pumped from the fields, the water is mixed according to the following rule:

Tab. 2-1 Supply water temperature regulation

Outside temp.	Water temp.
< -10 °C	>76 °C
-10 to -5 °C	74 to 76 °C
-5 to -0 °C	73 to 76 °C
0 to 5 °C	72 to 75 °C
5 to 10 °C	71 to 74 °C
> 10 °C	70 to 72 °C

There is not always a sufficient amount of return water to lower the temperature to the desired value. The requirement for minimum pressure of 1.3 bars in the return pipe also limits this amount. If the pressure went below that value, cavitation in equipment like radiators could occur (Norðurorka, 2009) (Árnason, 2009).

The amount of Glerárdalur water flowing into the lower storage tank is regulated by the valve situated at the CPS. It adjusts to the water level in the degassing tank at Glarardalur. If water in the degassing tank drops below some set level, the valve decreases the flow and the level rises. If the water level rises too high the valve opens more to let more water flow out from the degassing tank.
The amount of water flowing into Glerárdalur degassing tank from the borehole is regulated according to the inlet temperature of the water entering the lower storage tank. In cold winter periods this temperature should be around 80 °C and in warm summer days around 70 °C. If the inlet temperature to the lower tank is too high, the flow from the borehole increases and the water level in the degassing tank rises (Árnason, 2009).

The water level in the tank is kept constant. If it fluctuated, air would be sucked into the tank and would cause corrosion in the system. From the tank the water is pumped by two pumps to customers. These are two 14DOH Floway pumps with four stages. One of them is frequency regulated with a 150-hp, 1450 rpm motor and a maximum performance of 120 l/s at 55 Hz. The other pump has a 100- hp motor and a performance of 95 l/s (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

Water from Eyjafjörður and Glerárdalur mostly serves the needs of consumers in the lower part of the town, while water from Hjalteyri and Þelamörk mostly serves customers in the upper part of town. Depending on production from each field, water from the upper system can flow to the lower system through the pumping station and vice versa. If the level in the lower storage tank rises above 91.5 % the pump at CPS starts and the water from the tank flows to the upper system, either directly or through the upper storage tank. If the water level in the tank is between 89 and 91.5 %, the pump does not work and the valve (see figure) is closed. In the situation when the level is below 89%, the valve opens and water from the upper system flows to lower system (Árnason, 2009).

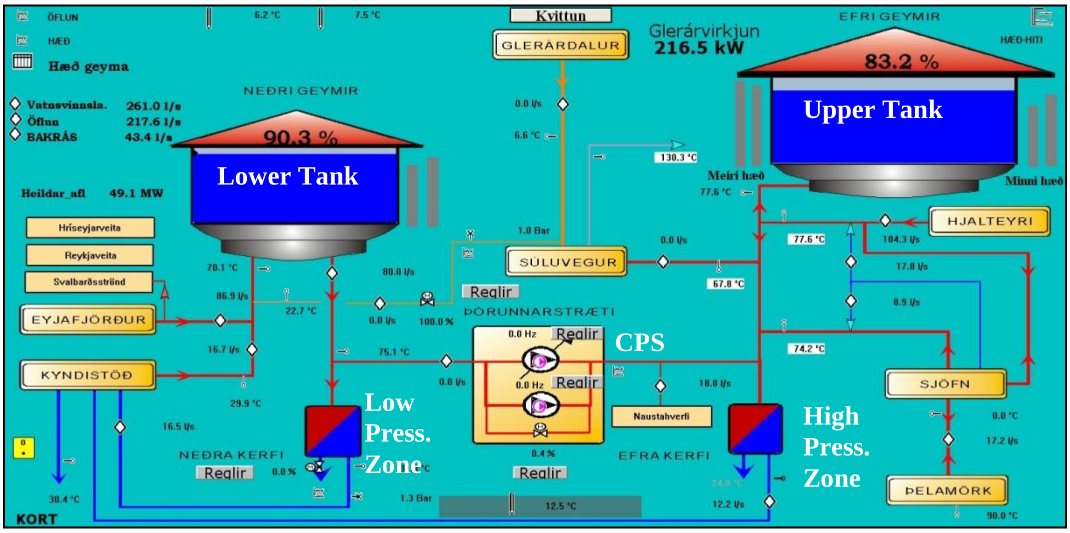

Fig. 2.10 Akureyri's heating distribution system (Scada)

In 1984, two 1.3-MW heat pumps were installed at the CPS. The purpose of the installation was to extract more energy from the geothermal water instead of discarding 27 °C hot return water. In the system, a part of the return water was cooled down to approximately 15 °C and the heat was transferred to what remains of the recollected return water (Flovenz, Ártnason, Finnsson, & Axelsson, 2000).

Heat pumps had been in operation until 2003, when Hjalteyri field begun to operate. Now they are used as a reserve and are switched on occasionally (Steindórsson, 2009).
The smaller one of the two electrical boilers installed at Akureyri is located at the CPS. The 1-MW boiler can be used to regulate the temperature of water from the CPS but is now out of commission.
The 12-MW oil burner uses heavy fuel oil. It is primarily used in emergency cases, such as in the event of major system failure. It has also occasionally been used over short and extremely cold periods in the winter time when more power is required than can be extracted from the geothermal fields (Steindórsson, 2009).

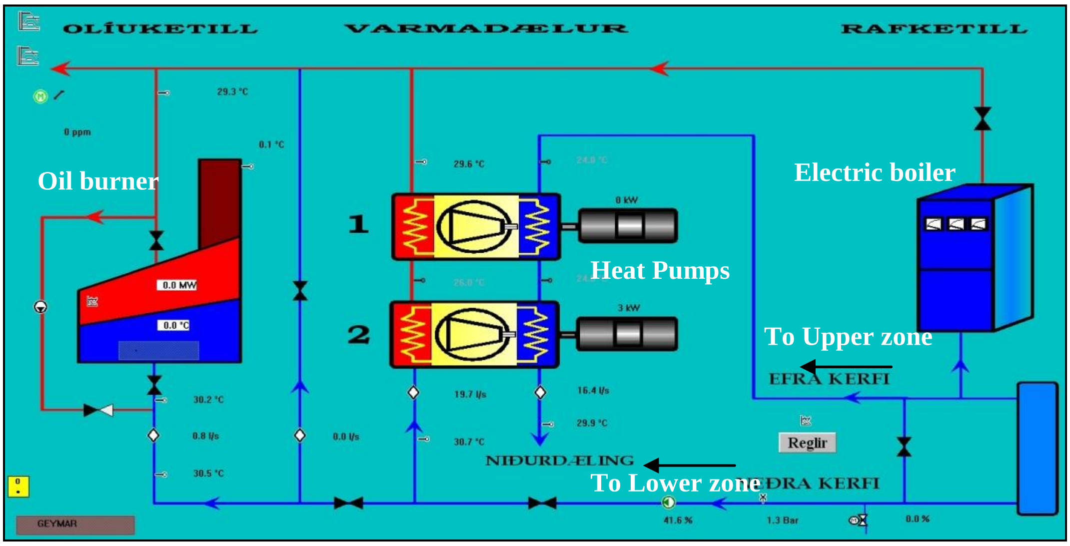

Fig. 2.11 Central Pumping Station (Scada)

2.4.2 Sjöfn station

At Sjöfn a portion of the return water (~27 °C) that has been recollected from buildings is mixed with hot water coming from Hjalteyri and Þelamörk fields. Water from Þelamörk has a temperature of approximately 88 °C when it enters the station. Water from Hjalteyri has a temperature above 80 °C (Árnason, 2009).

In the summer, when Þelamörk is out of use, a portion of the water from Hjalteyri is pumped by a small pump situated at Sjöfn towards Þelamörk and re-injected there (Steindórsson, 2009).

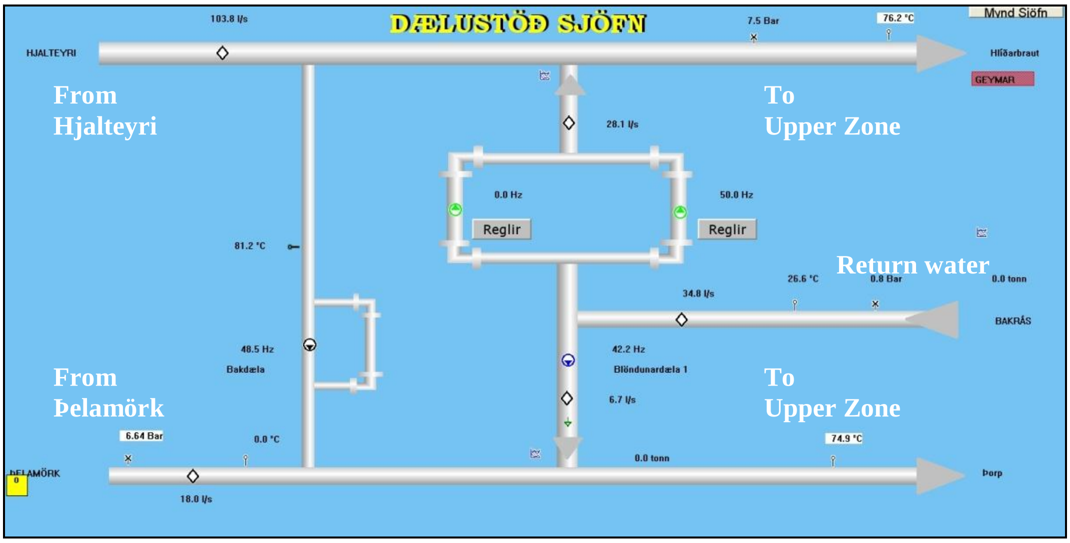

Fig. 2.12 Sjöfn station (Scada)

Sjöfn pumping station is not used to lift the pressure of water coming from fields. Pumps are used for mixing purpose and are installed only on pipes with return water. The pressure needed to transport the water from the fields to the users is provided by pump stations located at Þelamörk and Hjalteyri.
After being mixed with return water at Sjöfn, water from Þelamörk serves consumers in the high pressure zone of the system. Hjalteyri water goes to the upper part of the system towards upper storage tank, supplying consumers on the way (Árnason, 2009).

2.4.3 Upper storage tank and 'MS' dairy farm

A 5000-m3 upper storage tank is situated in the western part of town at 115 m above sea level. To avoid oxygen contamination, a blanket of steam, produced by the 6-MW boiler, is used to cover the water surface in the larger storage tank. This allows the amount of water in the tank to be changed (Steindórsson, 2009).

After being mixed with return water at Sjöfn, water from Hjalteyri has pressure above 7 bars. It flows in the direction of the upper tank serving consumers on the way. At one moment water cannot flow in and out of the upper storage tank. If more water is pumped from the fields than required to fulfill the demand, water flows into the upper storage tank. If the amount pumped from the fields is insufficient, water flows out of the tank to consumers. The system is run in such way that the water level in the storage tank is oscillating around some value. This means that water flows in and out periodically. The reason is that if the water level dropped too much, the costs of steam needed for the steam blanket would increase. The steam produced by 'MS' dairy farm is a rather expensive solution because of electricity costs (Steindórsson, 2009). At the inlet of steam to the tank a valve regulating the required amount is installed. In case of low demand for steam the valve decreases the steam inflow. Low flow could cause the steam to subcool, thus a bypass is mounted that ensures some minimum flow at all times (Fig. 2.13) (Árnason, 2009). The tank is made of steel and insulated by Rockwool (Steindórsson, 2009).

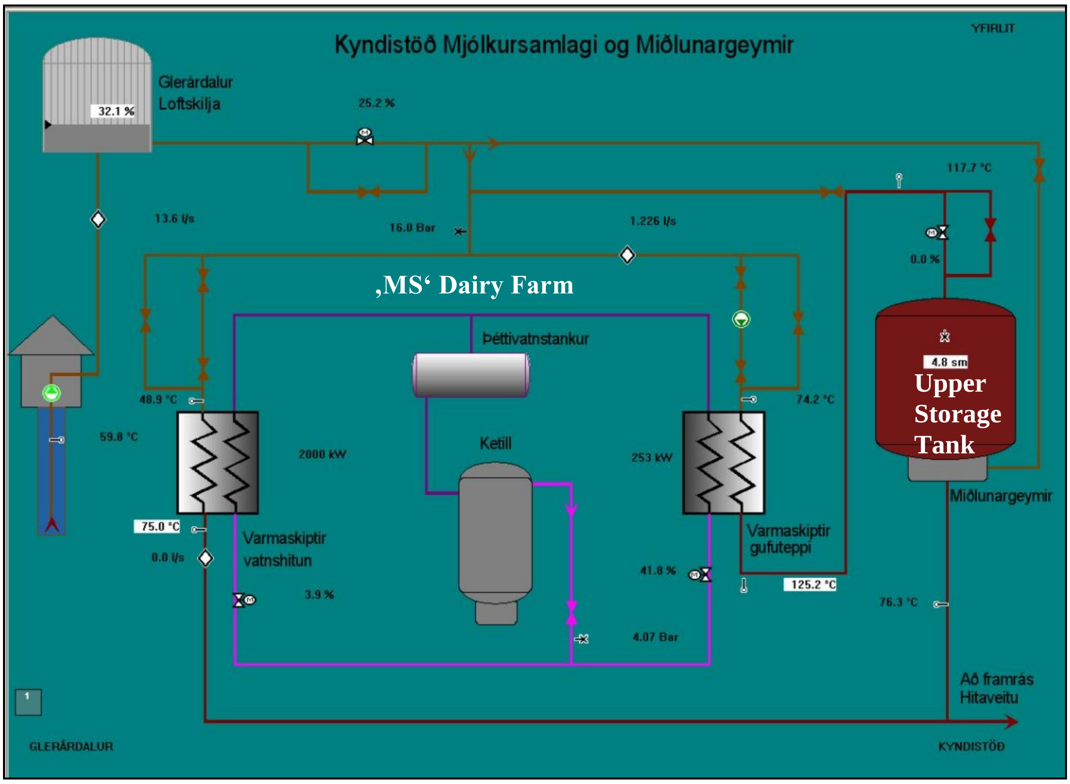

Fig. 2.13 Glerárdalur, 'MS' dairy farm and Upper Tank (Scada)

2.4.4 House stations

Within the buildings, the water enters a substation which includes a back-pressure control valve, a no-return control valve, flow meter, thermometer and a shut-off valve. The water is sold to the consumers according to volumetric measurements but corrections are made if the water temperature is below certain limits at maximum load (Flovenz, Ártnason, Finnsson, & Axelsson, 2000). During cold winter periods the temperature that reaches the consumers is between 60 and 80 °C. If the temperature of water reaching consumers is below 68 °C, the price of water is discounted according to following rule:

Tab. 2-2 Hot water discounting rules

Supply water temperature at consumer	Discount
66 °C	5%
64 °C	10%
62 °C	15%
60 °C	20%

Water temperature does not fall below 60 °C. In winter this temperature is secured with a bypass (Norðurorka, 2009).

2.4.5 Pipelines

In the newer parts of the city, modern pre-insulated steel and PEX pipes are installed. Currently Logstor pipes are used (Steindórsson, 2009).

2.5 Scada system

At Norðurorka, a Scada system is installed. The borehole pumps, pumps in the distribution system as well as valves are controlled remotely. The operator can read temperatures and pressures from the computer screen and react by changing valve and pump settings. Water level in tanks and frequency of pumps can also be read.
Scada is a very convenient tool for regulation since the operation of a system can be optimized all the time. Whenever the demand changes, the production of fields can be increased or decreased or water from tanks pumped into the system. The mixing of geothermal and return water is also regulated via Scada. The system has a user friendly interface. An example is presented in Fig. 2.14. Most of the figures showing the system layout are also taken from Scada system.

Fig. 2.14 Scada screen

2.6 Chemistry of waters

Generally the water is very low in chemical content (TDS = 190 - 290 ppm) and direct use should be possible without any problems (Norðurorka, 2009). Yet corrosion problems, especially in radiators, were encountered after a few years of operation. The corrosion was caused by oxygen contamination mainly originating in the storage tank, but partly in the degassers. A minor oxygen contamination will make the water corrosive. Therefore, its concentration should be kept below 10 ppb. A minor oxygen contamination in geothermal water is usually harmless as oxygen reacts with hydrogen sulphide in geothermal water to form sulphate. But since the water utilized in Akureyri is extremely low in H2S, it is necessary to mix sodium sulphide (Na2SO3) into the water to remove the oxygen. This mixing is not sufficient, however, to allow the use of the storage tank. The reaction is too slow to remove all oxygen before the water enters the houses closest to the tank. Hjalteyri is an exception. Water there has higher concentration of hydrogen sulphide and no additives are required (Flovenz, Ártnason, Finnsson, & Axelsson, 2000) (Steindórsson, 2009).

2.7 Geology

The crust around Akureyri is made of 6-10 m year old flood basalts inter-bedded with thin layers of sediments. The lava pile typically tilts a few degrees towards the active riftzone. The lava pile is intersected by numerous near-vertical dykes and normal faults, which appear in swarms. The lava pile has suffered low-grade alteration which, together with precipitation of alteration minerals, has drastically reduced the primary permeability. In recent geological times, crustal movements have caused the formation of tectronic fractures, which often coincide with older dykes or faults. Many of the low-temperature geothermal fields in Iceland are local convection systems situated in such fracture zones. Thus, the low-temperature geothermal systems of Iceland are, in most cases, fracture-dominated convection systems surrounded by almost impermeable rock. This is the case for five geothermal systems utilized by Hitaveita Akureyrar. The low-permeability and small volumes lead to a great pressure drawdown and limited productivity for the systems (Flovenz, Ártnason, Finnsson, & Axelsson, 2000). Hjalteyri geothermal field is of a different kind than the other five fields. The reservoir is much more productive because of its relatively greater volume and permeability. This makes Hjalteyri the most productive field supplying Akureyri's district heating system (Gautason, o.fl., 2005).

3 MATHEMATICAL DISTRICT HEATING MODELS

3.1 Simulation time scale

The purpose of mathematical models of district heating systems is to describe how the system behaves in time. The order of magnitude of time constant used in simulations of typical district heating systems is in days.

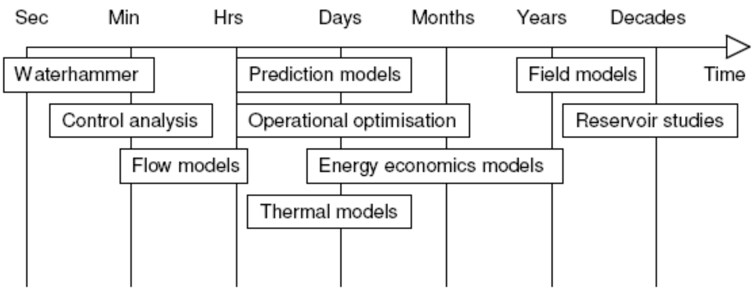

Fig. 3.1 Simulation time scale (Valdimarsson, 1993)

3.2 Models classification

District models are classified by type, method, approach and usage.
When classified by type, district heating models can be divided into macroscopic and microscopic.

3.2.1 Macroscopic vs. microscopic

Macroscopic models ignore the spatial structure of the system. The system is lumped into blocks. Output signals are related to relevant inputs. The distribution system and consumers are seen from the water supply station – seen from the viewpoint of the supplier.
In microscopic models the system is studied in detail both in time and space. This way water flow, pressure and temperature in all pipes of the system can be calculated as a function of time.

3.2.2 Dynamic vs. steady state

District heating models can also be divided into dynamic or steady state models. In a dynamic model the influence of the past on the present state of the system is taken into account. In the steady state method, steady state conditions are assumed which means that system behavior is not dependent on previous state history (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993).

3.2.3 Physical vs. black box

Model can be based either on a priori knowledge of the nature of the district heating system, or relations determined from measured data. The first approach is physical, which means that the base for modeling is thermodynamic knowledge of the behavior of the system. In the second approach the model is treated as a black box – a priori knowledge of the physics of the real system is used. These are statistical models and are used to calculate the model output signal as a function of the input and control signals by using some mathematically convenient structure.

3.2.4 Design vs. operational

Models can be used for design or operational optimization purposes. The design usage of a model refers to when the model is used primarily to study the design of a system, mainly by predicting system performance under various extreme conditions.
Operational usage of a model aims at fine tuning the operation of an existing system in order to improve its economy or performance.

3.3 Signals in simulation of district heating system

External physical variables that influence the performance and behavior of the system are called factors. Simulation implies that some time history is studied. Time histories of factors are called signals.
The response of the output signal to the input and control signals (external conditions) is the desired result of the simulation. In order to be able to perform the simulation the model relating these factors must be defined.
The factors influencing the system and their time histories are divided into independent factors, control factors, state variables and dependent factors.

3.3.1 Independent factors

Independent factors do not depend on the thermal state of the system nor on the actions of the district heating system operator. The weather is the main factor in this group. The time history of the independent factors is a model input signal. The real physical input signal to a district heating system is the heat lost from the buildings connected to the district heating system over to the ambient air. Meteorological signals like outdoor air temperature, wind velocity and direction, solar radiation and cloud coverage have influence on this heat loss, but their influence cannot be determined explicitly.

3.3.2 Control factors

Control factors are under the control of the district heating system operator. The system water supply temperature and the pressure in the distribution system pipes belong to this group. The time history of the control factors is a model control signal. The control signals are those which the system operator can change (within limits) to influence the state of the system. Supply temperature can be regulated via the mixing valve and pressure can change due to flow regulation.

3.3.3 State variables

State variables represent the dynamic elements of the system where energy is stored. They are dependent factors, but are taken here as an independent group because they are the only factors that are described by differential equations. State variables indicate energy stored in the system either as hot water in storage tanks, or as heat stored in the hot mass of the heated buildings. In addition to that, energy can be stored in the distribution system where the system supply temperature to the system can be controlled (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993).

3.3.4 Dependent factors

Dependent factors are determined by the other groups. Here the main factors are water flow and water return temperature. The time history of the dependent factors is a model output signal. The primary output signal from the fossil fuel fired district heating systems simulation models is the heat fed into the system at any time. The primary output signal from the geothermal district heating system models is the water flow to the system. This is due to a difference in the cost structure between these two system types. The fuel or the heat is a main cost factor in fossil fuel fired systems. The geothermal systems take their heat from geothermal water, and the cost of supplying the water (water extracted from wells) is close to being independent of the water temperature. The temperature of the hot thermal reservoirs also plays a role: the fossil fuel fired system has the hot reservoir in the flue gas of the boiler, whereas the geothermal system has the hot reservoir in the much colder geothermal field. This results in the need to maximize the radiator water cooling (and thus minimize the flow) in the geothermal district heating systems.

Tab. 3-1 Signals in district heating systems modeling

Input signals	**Control signals**	**State variables**	**Output signals**
Outdoor air temperature Wind velocity Wind direction Solar radiation Cloud coverage	System water supply temperature Water pressure	Indoor temperature Water quantity in storage	Water flow Return water temperature System heat load

The model parameters are dependent on the modeling approach selected, and are usually unknown. Some information on them can be obtained if the model is based on some known properties of the system. To obtain information on the model parameter values, parameter estimation is employed. A measured output signal over some period of time is compared with an output signal simulated from some set of model parameters and the measured input and control signals, which generated the measured output signal of the real system.
The parameter estimation process is then a process of varying the values of the model parameters until the simulated and measured output signals are in adequate agreement.
A score function is used to measure the difference between the simulated and measured output signal (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993).

3.4 Macroscopic model

The models treated here are macroscopic physical models. The district heating network is lumped into one model block, and the whole system is modeled as seen from a district heating water supply station. In order to be able to lump the system elements together, each of the elements has to be analyzed.
A reference or design condition is chosen which usually represents the design (maximum) load of the system. The design condition is referred to with the subscript $_0$.

3.4.1 Radiator

The radiator is the heat exchanger that transfers heat from the district heating network to the indoor air. The relative heat duty of a radiator can be written as:

$$\frac{Q_{rad}}{Q_0} = \left(\frac{\Delta T_m}{\Delta T_{m0}}\right)^{4/3} \tag{3.1}$$

The radiator logarithmic temperature difference ΔT_m is defined as:

$$\Delta T_m = \frac{(T_s - T_i) - (T_r - T_i)}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} = \frac{(T_s - T_r)}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \tag{3.2}$$

, where T_s is the temperature of water supplied; T_r – temperature of water returning from radiator; T_i – indoor temperature

Inserting equation (2) to equation (1), it becomes:

$$\frac{Q_{rad}}{Q_0} = \left(\frac{(T_s - T_r)}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \frac{1}{\Delta T_{m0}}\right)^{4/3} \tag{3.3}$$

This is the relative load of the radiator, normalized to the design condition.

3.4.2 Water heat duty

The heat duty, which the district heating water transfers over to the radiator surface, is:

$$Q_{water} = c_p m (T_s - T_r) \tag{3.4}$$

The relative water heat duty can be written as (Valdimarsson, 1993):

$$\frac{Q_{water}}{Q_0} = \frac{\mathrm{m}}{\mathrm{m}_0} \frac{T_s - T_r}{T_{s0} - T_{r0}} \tag{3.5}$$

3.4.3 Building heat loss

Heat loss from the buildings is defined as:

$$Q_{loss} = k_l(T_i - T_o) \tag{3.6}$$

, where the building heat loss factor k_l is a constant; T_i and T_o are indoor and outdoor temperatures respectively.

The relative heat loss is obtained as:

$$\frac{Q_{loss}}{Q_{loss0}} = \frac{T_i - T_0}{T_{i0} - T_{o0}} \tag{3.7}$$

3.4.4 Pipe heat loss

Some heat is lost in the pipes connecting the pumping station and the buildings to be heated. The amount of the loss can be calculated by using district heating pipe transmission effectiveness parameters. The transmission effectiveness τ is defined as:

$$\tau = \frac{T_s - T_g}{T_1 - T_g} = e^{-\frac{U_p}{mc_p}} \tag{3.8}$$

The reference value of τ can be calculated from the reference flow conditions:

$$\tau_0 = \frac{T_{s0} - T_g}{T_{10} - T_g} = e^{-\frac{U_p}{m_0 c_p}} \tag{3.9}$$

Parameters U_p and c_p are assumed to be constant all over the system. Combining the equation (8) and (9) the transmission effectiveness can be obtained:

$$\tau = \tau_0^{\frac{m}{m_0}} \tag{3.10}$$

Combining the equations (8) and (10) the supply temperature to the house can then be calculated (Valdimarsson, 1993).

$$T_s = T_g + (T_1 - T_g)\tau = T_g + (T_1 - T_g)\tau_0^{\frac{m_0}{m}} \qquad (3.11)$$

In the case of a return water pipe network the temperature of water coming back to pumping station is calculated in the same way. τ_0 for the return network has to be defined.

3.5 Microscopic model

3.5.1 Basic relations

Microscopic models can be used to describe the spatially distributed district heating system behavior. The goal of developing such models is to be able to calculate the water flow, pressure and temperature in all pipes of the distribution network as a function of time. Network theory provides convenient ways of determining the flow in a given network. The thermal state of the network can then be calculated from the flow solution.

Tab. 3-2 Solution of microscopic models

Calculated	Available data	Unknowns	Constraints
Water flow in all system elements Head at all nodes	Known flow in some elements Known head in some nodes	Element flow Head at the nodes	Kirchhoff's current law Kirchhoff's voltage law Elements (branch) relations

Kirchhoff's current law

The sum of the mass flows at any node equals 0 at any time. This results in one equation for each node:

$$\sum_{j=1}^{n_n} a_{ij}\, m_j = 0 \qquad (3.12)$$

Kirchhoff's voltage law

The sum of all voltage (potential) differences along any closed path (loop) in the network is zero. This results in one equation for each loop (Valdimarsson, 1993):

$$\sum_{j=1}^{n_n} b_{ij}\ h_j = 0 \qquad (3.13)$$

Element relations

The element relations add one equation for each element, relating flow and head loss:

$$h_j = f(m_j) \qquad (3.14)$$

This is the so-called resistance formulation, where $f(m_j)$ is a non-linear head loss function. This equation can be inverted in order to give the conductivity formulation:

$$m_j = g(h_j) \qquad (3.15)$$

Direct mass flow solution

A solution of these two sets of equations will give the flow in all elements. The head change and sub-sequentially the nodal head can be found from the element relations. The resistance formulation is used here.

$$\sum_{j=1}^{n_n} a_{ij}\ m_j = 0 \qquad (3.16)$$

$$\sum_{j=1}^{n_n} b_{ij}\ f(m_j) = 0 \qquad (3.17)$$

Direct head loss solution

A solution of these two sets of equations will give the head loss in all elements. The flow and sub-sequentially the nodal head can be found from the element relations. The conductivity formulation is used here (Valdimarsson, 1993).

$$\sum_{j=1}^{n_n} a_{ij}\, h^{-1}(h_j) = 0 \tag{3.18}$$

$$\sum_{j=1}^{n_n} b_{ij}\ h_j = 0 \tag{3.19}$$

3.5.2 General network theory analysis

When modeling a district heating network these basic laws have to be fulfilled:

- conservation of mass
- conservation of momentum
- conservation of energy

The graph theory considers a network to be a composite concept of:

- a set of nodes (x, y, z)
- a set of branches
- a connectivity relation (n_i, n_j)

The general network analysis follows the terminology commonly used in network theory. Path, connected graph, loop, tree, spanning tree, cutset, link and cotree are defined.

Element types

The flow solution of a network has three element types:

Tab. 3-3 Element types

Symbol	Element type
p	pipes
m	flow elements
h	head elements

Pipes stand for all fluid conduits. Besides pipes, other elements included in this group are pumps, valves and other fluid conduits. A pipe element is simply a set of serially connected physical elements in the network having some relation between flow and head change.

Flow elements have a constant, known flow. They are usually used to define the consumption point in the network, and therefore have one end connected to a datum or zero point.

Head elements have a constant, known head difference between the element connection points. They are often used to define a supply point and have than one end connected to a datum or zero point.

The connectivity matrix and relations

The incidence or connectivity relation relates each branch to a pair of nodes: the node where the branch originates and the node where it ends. A distribution system can be treated as a connected graph in which the pipes correspond to branches and the nodes to points where the pipes divide or are united, or convey the flow to the consumer.
In network theory an incidence (or connectivity) matrix must be defined in order to describe the above mentioned connectivity relation for a network with n_n nodes and n_f branches (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993):

Matrix A is an $n_n \cdot n_f$ matrix, with entries a_{ij} where:

- $a_{ij} = 1$ if pipe j starts at node i,
- $a_{ij} = -1$ if pipe j ends at node j,
- $a_{ij} = 0$ otherwise.

The connectivity matrix as defined above has one column for each flow stream in the system, and one row for each node. Each column can only have two non-zero entries, -1 and 1, as the flow stream has to originate somewhere and end at some other location.
A simple district heating system containing typical elements of such a system is shown in the next figure along with the associated connectivity matrix.

Continuity equation (Kirchhoff's current law)

Continuity for the mass in a pipe network can be defined by reference to the current law of Kirchhoff: 'The sum of the mass flows at any node equals 0 at any time.'

The connectivity matrix has a row for every node in the system. In each row all entries of 1 represent an outgoing flow stream from that node and entries of -1 an incoming flow stream. The system flow can conveniently be stated by means of a column vector with n_j entries, each stating the flow in the corresponding flow stream.
A positive flow indicates flow in the same direction as defined in the connectivity matrix, a minus sign indicates an opposite flow direction. By using the connectivity matrix this becomes:

$$Am = 0 \tag{3.20}$$

Momentum equations (Kirchhoff's voltage law)

The node piezometric head is conveniently stated in the column vector $\boldsymbol{h}_n$ with n_n entries, each stating the head at the corresponding node. As the connectivity matrix contains information on which flow streams connect to each node in the corresponding row, it is possible to calculate the head difference between the ends of all pipes in a vector form (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993):

$$\boldsymbol{A}^T \boldsymbol{h}_n = \boldsymbol{h} \tag{3.21}$$

4 STUDY CASE – SUPPLY TEMPERATURE OPTIMIZATION

4.1 Heating system in Naustahverfi

Naustahverfi is a district in Akureyri. It is situated in the southern part of town. It is a mainly residential area with one-family houses, rowhouses, multi-storey apartment buildings, summer houses and a school. It is supplied with heating and tap water from the Central Pumping Station. The temperature of the water leaving the pumping station is in the range of 65 – 85 °C. As in the rest of the city, there is one network for both heating and tap water. The water is pumped directly to all consumers in the district. There are no pumps between the Central Pumping Station and buildings. The water, after reaching the consumer, flows through a cubic meter which is read once a year and then to radiators or is consumed as tap water (Steindórsson, 2009) (Hjaltason, 2009). From the point of view of the network connections, Naustahverfi is isolated. All water that flows into the network goes to consumers within the district. The network has a tree structure. This means that the central pumping station is a root and houses (consumers) are the leaves. There are no loops. It is favorable design since there is no risk of water cooling in loops. It also makes the analysis of the system less complicated. After being consumed, water goes to sewage – in the case of tap water and the majority of heating water – or is recollected and pumped to the Central Pumping Station, where it is mixed with supply water from wells (Norðurorka, 2009).

The pipes in the district are supplied by Logstor Company. These are pre-insulated steel pipes and often PEX pipes for connecting houses. The standard connection for a single family house is DN 20 or bigger if there are more flats in the building, for example 4 flats usually take DN 25. The main pipe going from the Pumping station is DN450. The pipes are buried at a depth of 70 cm (Tryggvason, 2009).
In buildings, conventional radiators are installed and in some cases floor heating. Water returning from the radiator can also be used for snow melting.

4.2 Optimization criterion

The temperature of the water leaving the Central Pumping Station is regulated according to outdoor temperature. The reason is that it is outdoor temperature that determines the heat load of buildings and thus the flow in pipes. If the flow decreases, the transportation time and the heat loss to the ground increase. That is why it is profitable to pump colder water from the pumping station but with a higher flow rate during warm periods. When outdoor temperature is lower, the temperature of the supply water should increase. The temperature is adjusted by mixing hot water coming directly from the fields with cold return water. The rule for determining the temperature of the water was presented in Chapter 2.4.1, Tab. 2-1. Currently the supply water temperature (at the outlet from CPS) is adjusted by the operator. The idea is to design a running curve which could be followed by thermostatic valve, so the system functions optimally. A criterion of optimum system operation has to be chosen.

In the case of a fossil fueled heating system, fuel consumption would be such a criterion. A system operation would be optimal if it could satisfy demand with the lowest possible fuel use. It is analogical in the case of geothermal district heating. The factor to be minimized is the amount of water pumped from the fields (Valdimarsson, Modelling of Geothermal District Heating Systems, 1993). The more water is pumped from the fields, the sooner new, expensive drillings have to be made. Pumping from fields which are situated at long distances from town is also influenced by this water flow. The change in electricity consumption of the pump at the pumping station can be neglected (Steindórsson, 2009). The amount of energy delivered to houses is assumed to vary with outdoor temperature only – the influence of other atmospheric factors is marginal. Daily variations induced by the tap water consumption profile are also neglected. This is possible if daily values are used as an input. It can be assumed that daily tap water use is constant through the year. The conclusion is that the mixing temperature in the pumping station should be optimized as a function of outdoor temperature.

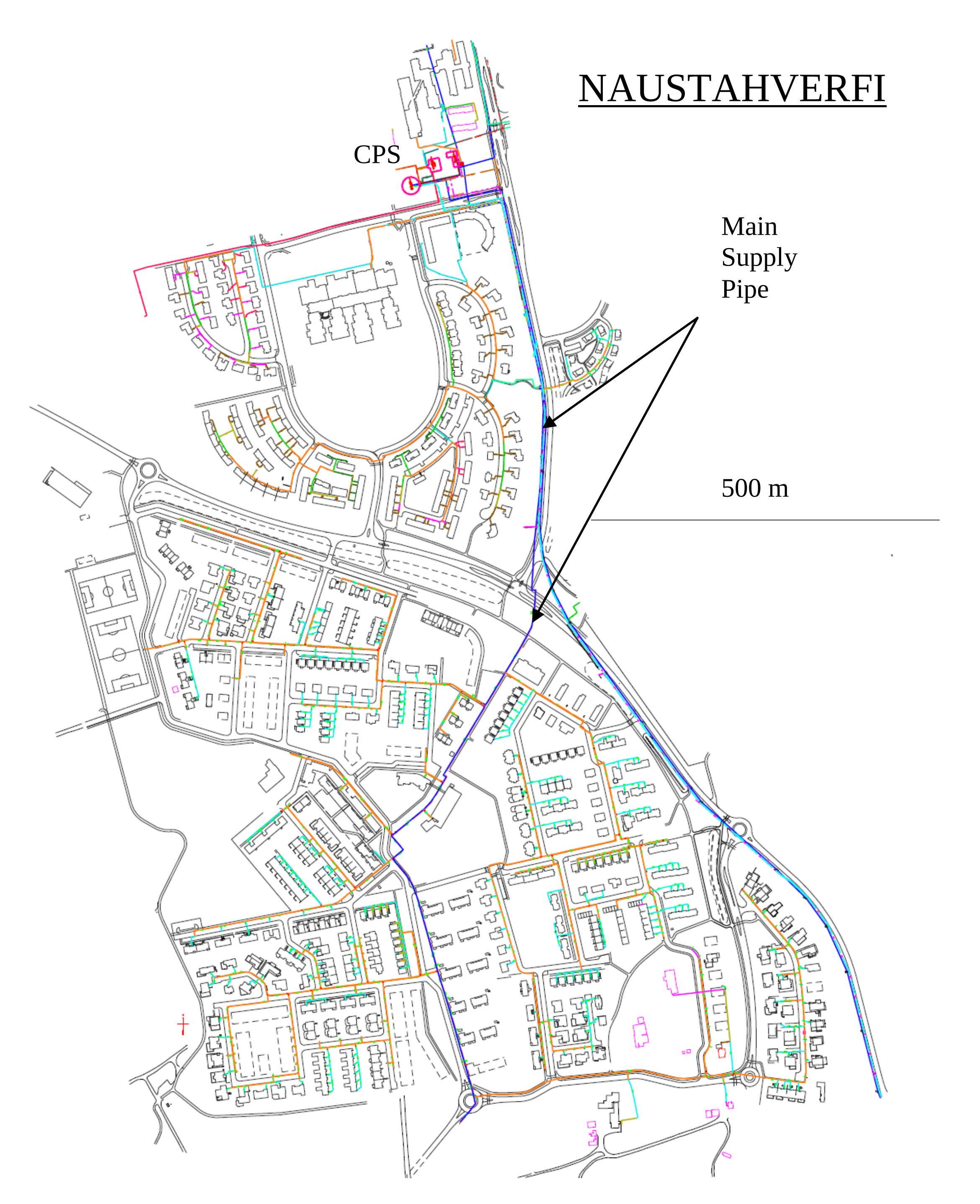

Fig. 4.1 Nausatahverfi's heating distribution system

4.3 Measurements

Data from Naustahverfi district is registered at the Central Pumping Station.
Water flow and water temperature measurements take place at the outlet from the pumping station towards Naustahverfi's consumers. Also, the return water temperature measurement is taken before it is blended with the water from fields. The return water comes not only from Naustahverfi but also from other districts. Outdoor temperature near the Central

Pumping station is also registered. All the data is collected in time rows. The measurements are taken with a very high frequency, every 5 minutes.
There are no time rows for individual consumers. The only data that can be obtained from consumers is the amount of cubic meters of hot water consumed per year. This is the sum of both heating and tap water (Norðurorka, 2009).

4.4 Data obtained

Norðurorka made the time rows of measurements as well as yearly readings from consumers' cubic meters available for this work. The number of people living at each address could also be obtained. The data comes from the year 2008.

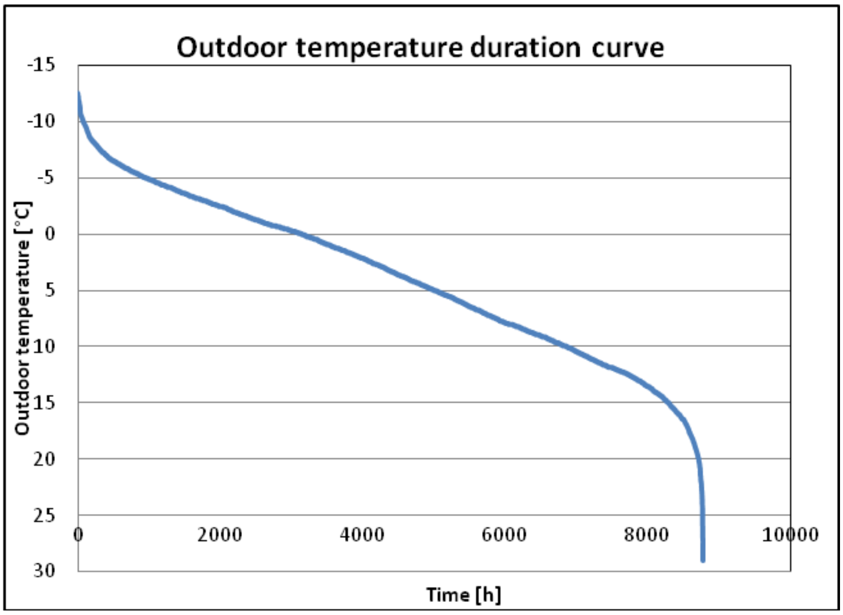

Fig. 4.2 Outdoor temperature duration curve, 2008

The outdoor temperature duration curve is flat, which reflects the nature of the Icelandic climate. There are only 60 hours with temperatures equal to or above 20 degrees. This means that the heating function of the system has to be provided virtually all year round. This is one of the reasons there is one distribution system for both tap and heating water.
Temperatures equal to or below -10 also are not common and cold waves are short, which is advantageous from the point of view of system dimensioning.

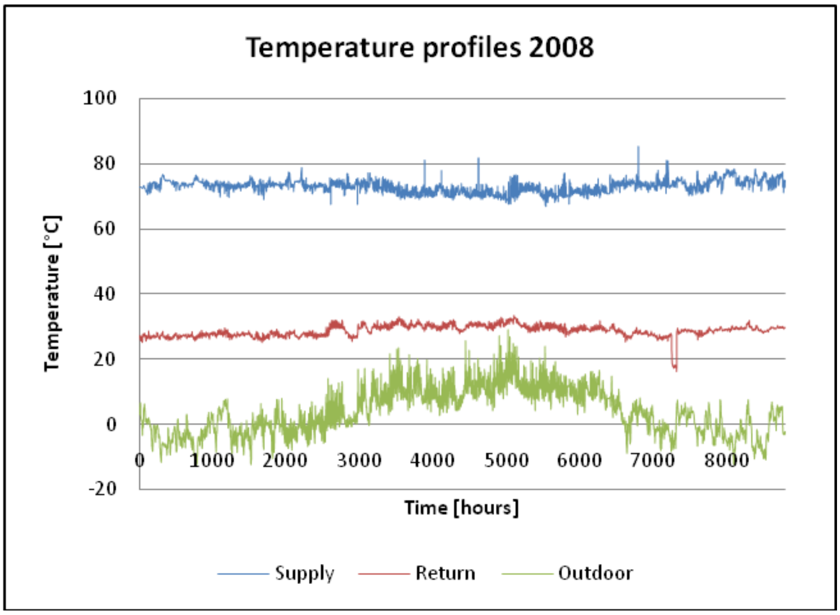

Fig. 4.3 Recorded temperature profiles, 2008

In the graph it is visible that the supply temperature at the station is normally between 70 and 78 °C, which is dictated by the rules for regulation of mixed water temperature.
The return water profile is not typical because normally the temperature should be lower during summer than in winter. In this case it is opposite. Possible reasons will be explained later.

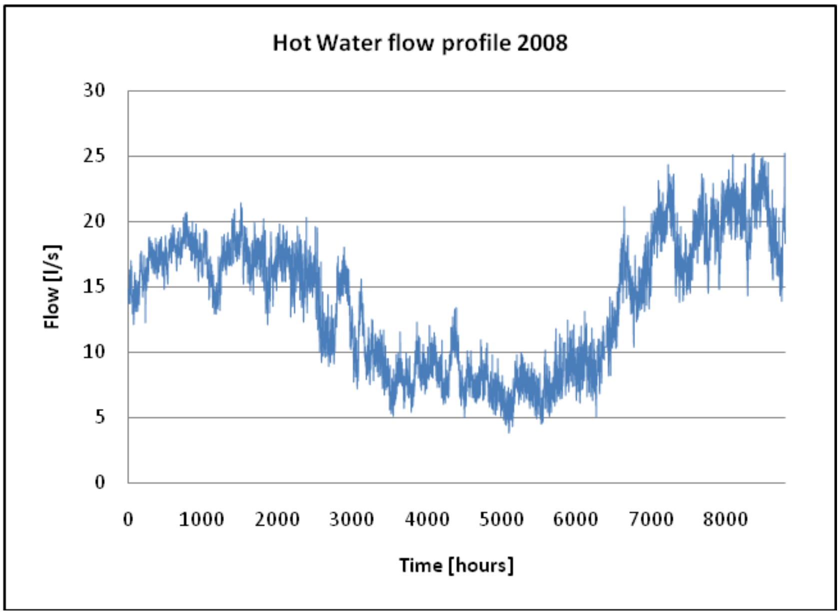

Fig. 4.4 Supply water flow profile, 2008

On the graph, the increase of flowat the end of the year relative to the beginning is visible. This is the disadvantage when analyzing new districts. Naustahverfi was still expanding in the year 2008. From the data obtained from Norðurorka, a slight growth was visible.

4.5 Choice of the model

A macroscopic model of a district heating system neglects the spatial distribution of the pipe network and consumers. It does not require knowledge of design details and measurements at each building. The system is viewed from the pumping station and its elements are lumped into supply and return pipe and a single user (Valdimarsson, 1993). A macroscopic model was chosen for the system optimization. The input data to the model would be outdoor temperature and the output would be the consumption of hot geothermal water from fields.

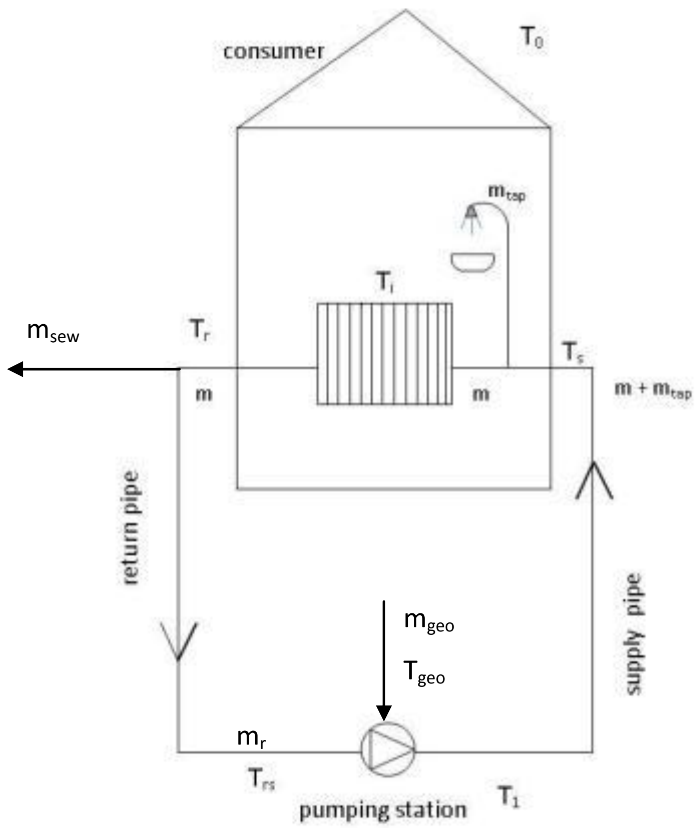

Fig. 4.5 Simplified layout of a district heating system

Fig. 4.5 shows how the system is simplified in a macroscopic model. Return water at CPS comes not only from Naustahverfi but also from other districts.

T_1, T_{rs}, T_s, T_r, T_i, T_o are the supply and return water temperature at the pumping station; supply and return temperature at buildings; indoor and outdoor temperature respectively.

m, m_{tap}, m_{geo}, m_{sew}, m_r are heating, tap, geothermal, disposed and recollected water flow rates respectively.

4.6 Data preparation

To build the model, reference values have to be known. Reference parameters (subscript $_0$) are the values of supply and return water temperature to the radiator (T_{s0} and T_{r0}); outdoor temperature T_{o0}, transmission effectiveness τ_0 and τ_{0r} (supply and return), and water flow m_0. T_{i0} is the reference indoor temperature and is assumed to have a constant value of 20 °C. These values are used when designing the system. They are different from region to region since the dimensioning of the system depends on climatic conditions and the kind of system. In Reykjavik T_{o0}=80 °C, T_{r0}=40 °C, T_{i0}=20 °C and T_{o0}=-15 °C are used as a standard (Valdimarsson, 1993). Standards in Akureyri are different because radiators of bigger size are used (Valdimarsson, 2009). That is why values from Reykjavik could not be used. Parameter identification had to be carried out.

Vectors of the supply water temperature T_1 and flow m_0 at the pumping station as well as the outdoor temperature T_{o0} were used as inputs to the model. The data time rows from year 2008 were averaged to obtain daily values except for m_0, where the value for each day was taken at 2 a.m., when the tap water consumption can be assumed $_0$. The average tap water consumption was around 1l/s for the district and was assumed constant through the year (Valdimarsson, 1993).
Fig. 4.6 shows radiator and tap water flows after separation for a sample 40 day period.

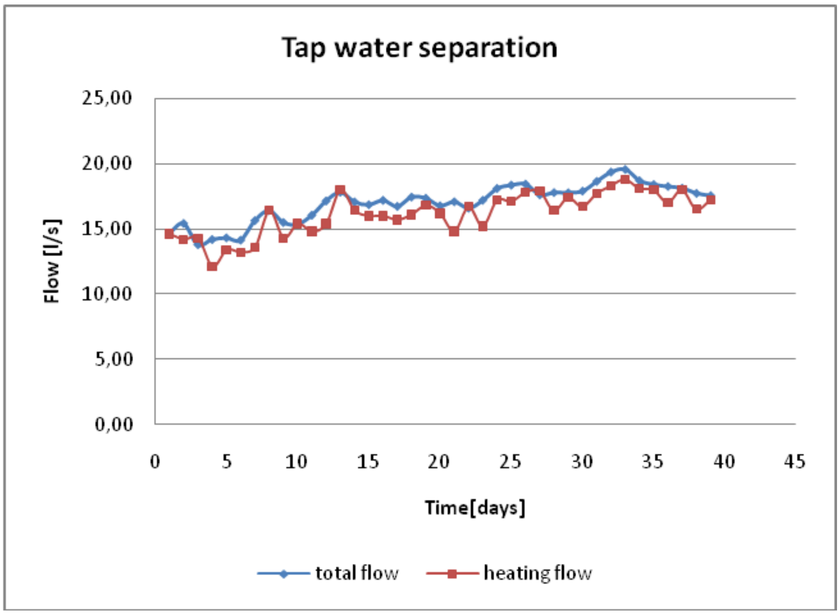

Fig. 4.6 Tap water separation

In some cases the daily average water flow from the pumping station is lower than the flow at 2 a.m. It causes negative values of tap water flow for some data points. This can be tolerated and a choice of zero tap water consumption at 2 a.m. is the best solution. There are two other methods. In the first, zero tap water flow is assumed at minimum flow during each day. In the second one, variation of the water flow around the daily average is studied. In those cases the results are worse (Valdimarsson, 1993).

Each vector has 366 elements, storing average values for one year. The vector of return water temperature back at the station T_{rs} is the output. It was compared with the measured value. An assumption had to be made, that the measured return temperature that comes from a part of town bigger than Naustahverfi is equal to the return temperature from the modeled district.
A steady state was assumed since the time constant for building is around 20 hours and data for the model was averaged to daily values. (Valdimarsson, 2009)

4.7 Parameter's estimation

Three relations were used for the identification of parameters.

Equation 3.11 for heat loss in supply pipe:

$$T_s = T_g + (T_1 - T_g)\tau = T_g + (T_1 - T_g)\tau_0^{\frac{m_0}{m}}$$

Steady state implies:

$$\frac{Q_{rad}}{Q_0} = \left(\frac{(T_s - T_r)}{\ln\left(\frac{T_s - T_i}{T_r - T_i}\right)} \frac{1}{\Delta T_{m0}} \right)^{4/3} = \frac{T_i - T_0}{T_{i0} - T_{o0}} \tag{4.1}$$

An equation for heat lost in the return pipe:

$$T_{rs} = T_g + (T_r - T_g)\tau_r = T_g + (T_r - T_g)\tau_{0r}^{\frac{m_0}{m}} \tag{4.2}$$

Tg is the temperature of the ground surrounding the pipes and is assumed to be constant with a value of 3 °C. Ti is the momentary value of indoor temperature and is also assumed constant with a value of 20 °C. During warm periods, when outdoor temperature exceeds 20 °C, fixing the indoor temperature at 20 °C would result in negative heat load. This is not a case when daily averages are taken as an input to the model since the daily average was never higher than 20 °C.

A score function is defined as follows (Valdimarsson, 1993):

$$V = \frac{1}{N}\sum_{i=1}^{N}(T_{rs}(i) - T_{rsm}(i))^2 \tag{4.3}$$

, where N equals 366, which is the number of data points (days). $T_{rsm}(i)$ is the vector of measured values.

A code in Matlab was built to minimize the score function and obtain reference parameters. The Fminsearch function using the Nelder-Mead algorithm was used. The minimization did not give any reasonable results. The conclusion was that the problem lies in the data used.

The profile of return water temperature at the station is not typical (Fig. 4.3). Return water temperature is lower in the winter and higher in the summer. The reason is that there are snow melting installations in many big buildings. The return water from the radiators does not go directly to the pumping station but is first used to melt the snow. This means that it

will return with lowered temperature. Floor heating, installed in many houses, also increases the temperature drop at the consumer (Steindórsson, 2009). There is also one more possible reason for this abnormal behavior of system.
It is very common in Akureyri to lay the supply and return pipe in pairs so that they are very close to each other, enabling heat transfer from the supply to the return pipe (Valdimarsson, 1993). These factors make it impossible to use return water temperature data for a macroscopic model.
The assumption that enables the use of return water data from different parts of town could also influence the calculations.

To obtain parameter values, a macroscopic model ignoring return temperature data had to be built. It was assumed that there are no heat losses in the return network. Equation 3.11 for heat loss in the supply pipe and equation 4.1 were used.

In the steady state model there is no storage of energy in the building, so the heat transferred from the radiator to indoor air (equation 3.4) is equal to heat loss to the outside (equation 3.6). These two values were compared to obtain reference parameters.

$$Q_{water} = c_p m(T_s - T_r) = k_l(T_i - T_o) = Q_{loss}$$

A score function is defined as follows:

$$V = \frac{1}{N}\sum_{i=1}^{N}(Q_{water}(i) - Q_{loss}(i))^2 \qquad (4.4)$$

The supply temperature to the radiator and the flow through the radiator are related so reference values for both parameters could not be obtained at once. The supply temperature had to be fixed. The same situation occurs with outdoor temperature and flow. The dependence can be seen on a scatter diagram Fig. 4.7.

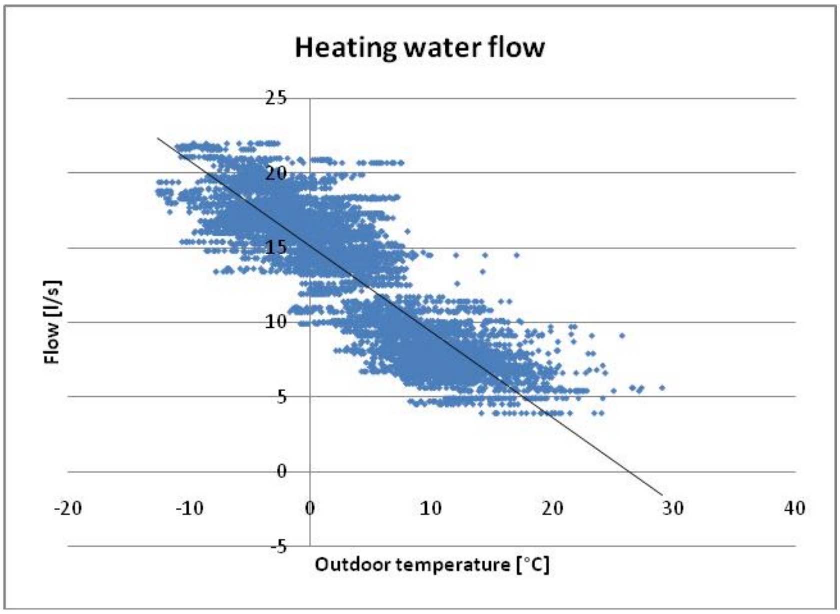

Fig. 4.7 Heating water flow scatter diagram

Heating systems in Akureyri are dimensioned for 75 °C inlet temperature and this value was assumed for T_{s0}. k_l=150kW/°C (Valdimarsson, 2009).
The outdoor temperature reference value for the design of heating systems in Akureyri is -15 °C (Norðurorka)(Steindórsson, 2009). This was taken as T_{o0} value for Naustahverfi. From the scatter diagram (Fig. 4.7), the reference value of flow was read: m_0 = 23 l/s.
The next step was to run the parameter estimation algorithm with T_{s0}, T_{o0}, m_0 and k_l values fixed. The score function had its minimum for τ_0 = 0.95 and T_{r0} = 35 °C. The values are realistic.

4.8 Optimization

The optimization criterion was defined in Chapter 4.2 as the lowest possible usage of hot geothermal water from fields. Before performing the simulation, the data had to be prepared. From a scatter of points, a more useful data had to be made. The scatter with respect to outdoor temperature was reduced. Matlab code was written. The vector of heating water flow was adjusted to make Q_{water} and Q_{loss} equal.
The result can be seen in Fig. 4.8.

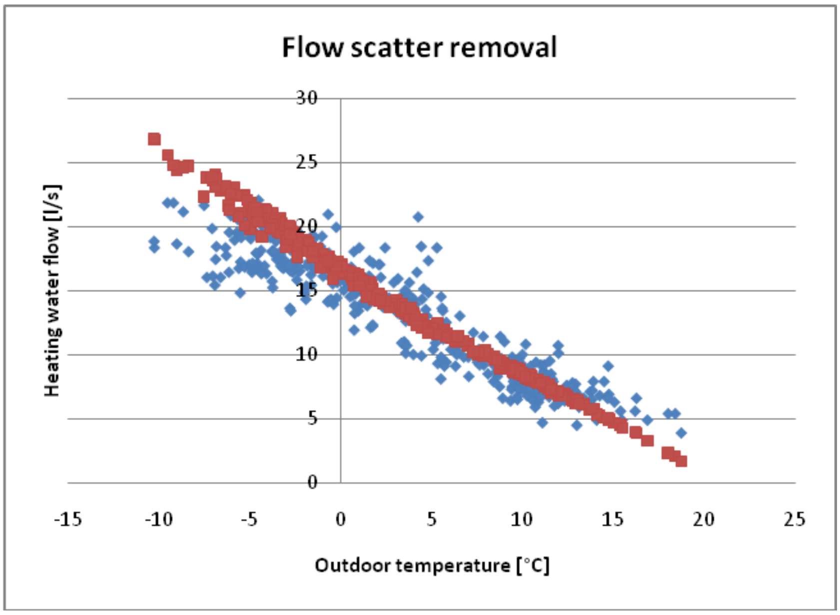

Fig. 4.8 Flow scatter removal

The flow of geothermal water to the system can be expressed by combining weighted temperature averages in the mixing and mass flow conservation of water:

$$m_{geo} = \frac{(T_{rs} - T_1)(m + m_{tap})}{T_{rs} - T_{geo}} \tag{4.5}$$

Geothermal water temperature T_{geo} was assumed to be 80 °C. Return temperature from the radiator is equal to the return temperature at the pumping station, so $T_{rs} = T_r$:

$$m_{geo} = \frac{(T_r - T_1)(m + m_{tap})}{T_r - T_{geo}} \tag{4.6}$$

An algorithm minimizing m_{geo} was written in Matlab. Different running curves were tested to obtain the minimum amount of geothermal water fed to the system during one year. The algorithm returned parameters of curves for which the consumption of geothermal water was lowest. There were limits in the optimization. The lowest supply temperature to a user was set at 50 °C and maximum supply temperature at the station Ts was limited to 80 °C (Valdimarsson, 2009). Such a temperature is very high for tap use but it was used in the actual system and people living in Iceland are used to it.
An optimum curve was obtained.

Tab. 4-1 Running curve points

T_o°C	-15 -9	-8.0	-7.0	-6,0	-5.0	-4.0	-3.0	-2.0	-1.0	0.0	1.0	2.0	3.0	4.0	5.0
T_1°C	80.0	79.9	79.8	79.7	79.6	79.5	79.3	79.1	78.9	78.7	78.4	78.1	77.8	77.5	77.2
T_o°C	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	19.0	20.0
T_1°C	76.8	76.4	76.0	75.6	75.1	74.6	74.1	73.6	73.1	72.5	71.9	71.3	70.7	70.0	69.3

Fig. 4.9 shows supply and return temperatures at consumer.

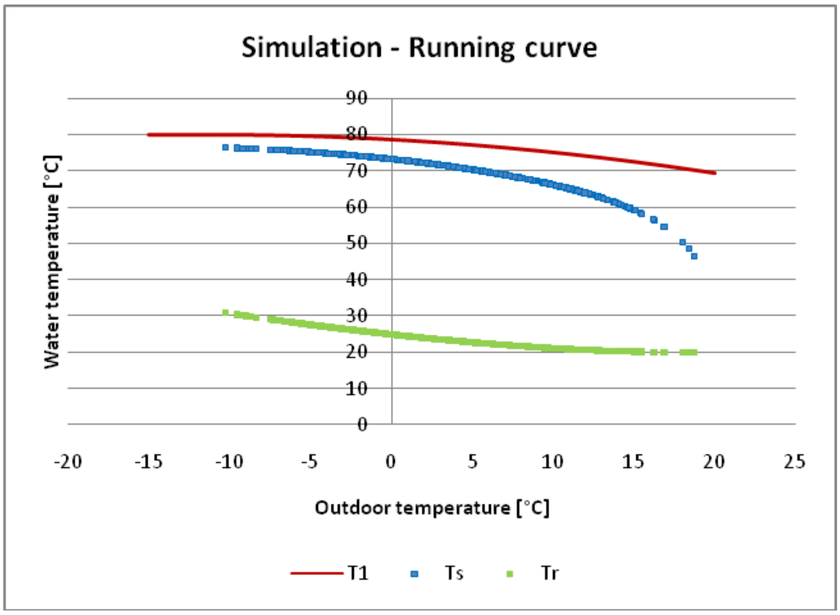

Fig. 4.9 Simulation with running curve

Only two points where supply water temperature T_s dropped below 50 °C occurred. Since macroscopic models give results for the worst situated user, the result is acceptable.

It is visible that return water temperature T_r is too low. This is due to the assumptions that had to be made because of unsuitable data for return water temperature at the station T_{rsm}.

In reality the return temperature from radiator T_r would be higher. The T_r temperature calculated with the same model from actual 2008 data is even lower (Fig. 4.10) which allows the assumption that in the optimized case it will be sufficient.

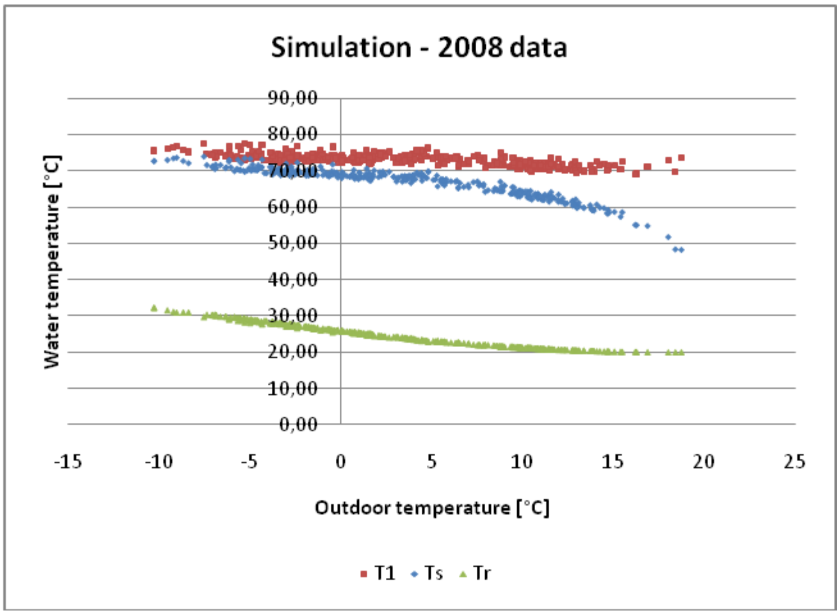

Fig. 4.10 Simulation with 2008 data

A comparison showing the curve obtained and actual data from year 2008 are shown on the Fig. 4.11.

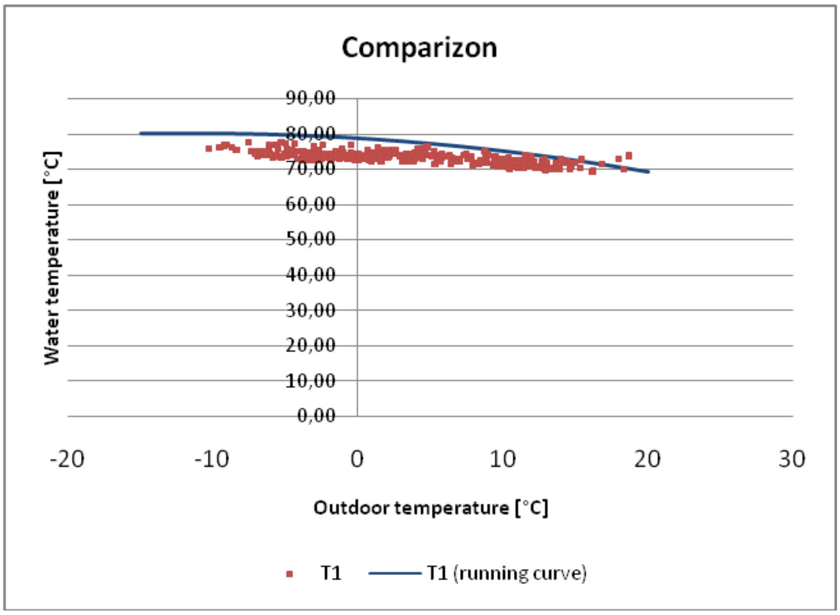

Fig. 4.11 Regulation comparison

The supply temperature T_1 resulting from optimization is higher than was read from actual 2008 data but the trend is similar and reflects the physics of the system. It is visible that the supply temperature should be higher in cold periods and lower in warm.

Geothermal water savings vary when using the running curve obtained. In 2008 the total consumption of geothermal water was 381632 tons. To compare this number to consumption when using the running curve, the flow has to be converted (the running curve was created using scatter-free flow). When recalculated with the modified flow the number becomes 410604 tons per year. The consumption, when using the running curve, is 409154 tons per year. The savings are around 0.4% and are marginal. This is probably the fault of assumptions made to overcome the problem with a lack of proper return temperature data.

The qualitative results are correct but the quantitative are doubtful. While the consumption is varied very slightly, it is clear that it should be low in the summer and high in winter. What is more, the consumption is much more sensitive to changes in temperature during winter time, which is the same as in reality. The flow in the winter is much higher and thus manipulating the supply temperature in this period induces much bigger changes in yearly consumption.

4.9 Microscopic model – an attempt

At the beginning a microscopic model approach was chosen. In the case of Naustahverfi, which is a small and quite homogenous district with around 1600 inhabitants, the number of nodes was 800. Not all data on the drawings was up to date. Connections of some buildings weren't shown; some pipes didn't have dimension data, etc. What is more, the real design of a district heating system always differs from the project. Some problems are encountered during the construction. For example, the different course of a pipe has to be chosen. What is more, when the system has been working for some time, changes are made to adjust the operation and correct design mistakes, or they can occur on their own, i.e. pipe ageing.

Despite the potential difficulties, Naustahverfi is still a very well documented design. It is a new district, modern pre-insulated pipes have been installed and their specification can be easily found in the internet. The situation would be much worse if it was an old district, i.e. a part of the system that was designed in the late seventies. The data would be on paper and hand drawings would be used. Lack of some information, like the elevation of pipes, is also obvious. It is doubtful that the actual installation would match the project anyway. In the beginning of geothermal utilization there was no experience with district heating in Akureyri. Many modifications to the system have been made. The system was constructed according to a trial-and-error method (Steindórsson, 2009).

The data available for Naustahverfi district was not sufficient for straightforward modeling. There was no data on flow or temperature at consumers, which is the case in most situations encountered in district heating modeling. Only yearly readings from cubic meters were available but they combined water for heating and tap purposes. Information on number of people living at each address was required to separate those uses. Assumptions of the daily consumption of a person had to be made. Sometimes a cubic meter was measuring the consumption of few apartments, where some of them were connected to the network during the simulation period. This complicated the analysis.

The result was that a lot of assumptions had to be made in the model that was supposed to be built according to a detailed knowledge of the design. Strength is always determined by the strength of the weakest link and in this case it was the strength of the assumptions made. This was the reason to abandon the microscopic model approach. In case of the inability to precisely model the structure, precise results cannot be expected. The macroscopic model was chosen, where the data on spatial distribution of the system is not used.

5 CONCLUSIONS

The computer is a very powerful tool in all kinds of engineering works. Computer modeling and simulation allow continuous testing of the design and modifications to it in order to get the optimum. The result can be very precise, especially when used with high quality data. There are many examples of successful implementation of modeling in district heating. Macroscopic models simplify the system by lumping it to one equivalent consumer connected to a pumping station. Compared to a microscopic model, this is a very convenient way to analyze a system because a detailed design study is not required. Acquisition of such data is a very time consuming process. Even in the case of new systems it requires a lot of work. Pipe lengths, dimensions and coordinates have to be determined. Other problems occurred during model construction (Chapter 4.9).

In the case of the macroscopic model, difficulties concerning data also occurred but they were of a different kind than in the microscopic model. The problem was not the lack of data, nor its quality. The problem was in the suitability. The data showed an atypical profile of return water temperature which was low in the winter and high in the summer. This was diagnosed as an influence of floor heating and snow melting installations, and the fact that return water comes from other districts. The macroscopic model assumes the same behavior of all radiators in the analyzed system. They have similar supply and return temperatures which are related to the heat loss of a building. Floor heating and snow melting, which are installed in some buildings, change the return temperature compared to a conventional radiator installation. If such installations were used only in a small amount of buildings, such influence could be neglected. The reality is different because in Akureyri snow melting is quite popular and, what is more, it is installed in big buildings from which the return water is recollected. It is the recollected water the temperature of which is registered in the pumping station.

Additional cooling of the water in the snow-melting and floor heating installations could be taken up by an additional parameter in the pipe heat loss analysis, dependent on outside temperature, i.e. variable ground temperature through the year; but this is a very complicated task and it was not investigated.

In these circumstances the macroscopic modeling theory is not applicable and the return data cannot be used. An approach to overcome the problem of unsuitable data was taken. A model ignoring these data was made and the transmission effectiveness in the return network was assumed to be 1, which means that there are no heat losses to the ground. This can be justified by the fact that return and supply pipes are often laid parallel so the heat transfer to the return pipe occurs. Parameter dependence caused by a lack of return temperature input was another obstacle. Some reference parameters were assumed based on engineering practices in district heating in Akureyri. This made it possible to find reminding parameters, which turned out to have reasonable values, and perform the optimization.

The system was simulated with different types of curves and the one giving the smallest geothermal water consumption during the year was found. The consumption varied very little when the system was subjected to different supply temperature curves, which may indicate some error; but the optimal curve is similar in its trend to the actual supply temperature data from 2008. What is more, a change in its course in the winter has a bigger influence on geothermal water consumption than a change in the summer. These facts support that the running curve can be treated as a general indication of how the system should be operated.

In the winter the supply temperature T_1 at the station should be close to 80 °C, which was set as the upper limit. If users had tap water heat exchangers, the supply water temperature could be even higher but the whole efficiency would decrease due to exergy loss, thus an analysis should be carried out in such a case. Another factor is the available temperature of geothermal water, which is not constant through the year.
The supply temperature in warm periods - when the demand and flow decreases - should be lowered to limit heat loss in the pipes. Here a second limit was set. The supply water at the consumer has to be at least 50 °C to be suitable for tap use.

This work was supposed to be the solution to an engineering problem but it turned out to be an assessment of different approaches in district heating modeling. Problems related to modeling of systems that include modern installations like floor heating or snow melting were revealed and addressed in the analysis.
It shows that even very high quality data can be of little use if not suitable for analysis.
The engineering problem itself is at least partially solved since it shows that the regulation principles at Norðurorka are generally good. The conclusion is that the temperature should be slightly higher in winter compared to how it is regulated currently.
If the geothermal water consumption results are correct, lowering the temperature in the summer is not very profitable and it might be better to send warmer water to consumers to increase their comfort related to availability of hot tap water.

6 SUGGESTIONS FOR FURTHER WORKS

The return water from the radiators still carries some energy when leaving a building, which cannot be transferred to the interior. It can still be utilized outside the building to melt the snow on the pavement or driveway. Akureyri is not a single example of a town where such installations are used. Snow melting is gaining popularity in Iceland and other countries.

Normally, return water at the pumping station should have temperature around 30 °C, higher in the winter and lower in the summer. In the case studied it was opposite. Snow melting installations, to fulfill their function, have to be laid at a shallow depth. The pipes are mounted around 10cm below the surface. This means that equation 4.2 for the heat loss in the return pipe is not valid because the heat loss to the ground depends on outdoor temperature (it was assumed that ground temperature T_g is constant at a depth of 70 cm). The water returning from snow melting installations can have temperatures as low as 5 °C. If the amount of recollected snow melting water is substantial it will seriously influence the return temperature profile at pumping station.

Fig. 6.1 Snow melting installation (Valdimarsson, 2008)

The work revealed the limits of the theory currently used in district heating modeling. The macroscopic model could not deal with an atypical return water profile caused mainly by snow melting installations. They were installed in many buildings where return water is recollected.

To solve the problem the current theory has to be corrected. Additional water cooling has to be included in the return water temperature calculation. This requires a study of the behavior of snow melting installations. A possible way of including the additional cooling would be introducing dependence on outside temperature to the return water temperature calculation at the pumping station (equation 4.2). This also would have to take into account the percentage of recollected water used for snow melting, so knowledge on the area of snow melting installations in the town as well as how they are operated has to be gained.

Even if a proper theory on snow melting was developed, it would not solve the problem that the return water reaching the pumping station comes not only from Naustahverfi but also from other districts, including a big swimming pool. What is more, there is a substantial amount of users who have floor heating installed.
In this particular case it would be a better idea to model the water cooling in buildings, based on measurements taken in a number of representative houses in the district. The return water data from the pumping station would not be used. There is a possibility to temporarily install meters in buildings and obtain temperature time rows. The resultant return water temperature profile would be obtained from those measurements.

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