Simulation of distribution system for low temperature district heating in future urban areas – Case study of a planned city district in Gävle

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Abstract

In Europe, the prices of natural gas and electricity reached an all-time high in 2022. A way to mitigate high electricity costs is to expand district heating systems in urban areas, this will reduce electric load as well as increase the power generation possibilities in combined heat and power plants. District heating has been the dominant heat supply technology in urban areas in Sweden since the 1980s. However, as the energy efficiency in buildings increase, district heating distribution losses must be reduced to ensure a cost-efficient heat supply. This has led to the idea of the 4th-generation district heating which is characterized by low distribution temperatures. In this study, low-temperature district heating distribution in a planned future city district is simulated using a Python-based tool. Two different low-temperature distribution systems are investigated: 1) 2-pipe low-temperature system, and 2) a cascading 3-pipe low-temperature system. The focus is on simulating the distribution losses, temperature drop, and mass flow in the pipe network. The scope of the analysis also includes an investigation of the effect of lower return temperatures on the central district heating network. The results indicate that the low-temperature distribution system with the 2-pipe system performs better than the cascading system when considering distribution losses and temperature drop. The mass flow depends on the temperature demand in the heating systems in the buildings and is considerably high for both low-temperature distribution systems investigated.

1 Introduction

In Europe, record-high electricity and natural gas prices were noted in 2022. Several countries within the EU have introduced financial instruments and subsidies to hamper consequences of high energy prices (Eurostat, 2023). These are, however, short-term solutions that are not necessarily sustainable in the long run, this as the dependence on fossil fuel imports remains. A more long-term solution is to develop energy systems to be more efficient and thus reduce dependence on fossil fuels. A possible way to reduce the urban need for electricity and natural gas is to replace conventional gas- and electric heaters in buildings with district heating systems (DHS). A measure that would also enable increased co-production of electricity in combined heat and power plants and thereby yield an increased overall system efficiency (Colmenar-Santos et al., 2016).

DH development has traditionally aimed to reduce heat distribution temperatures in order to reduce distribution losses, which is likely to be of further importance as the share of new low-energy buildings increases meaning that distribution losses tend to increase relative the heat demand. The concept of ”4^{th}-generation district heating” that was introduced by Lund et al. (Lund et al., 2014) is based on distribution temperatures below 70°C in order to deal with the challenge of a future high share of energy-efficient buildings.

The structures of DH networks in cities differs significantly depending on the local conditions. Access to industrial waste heat and the need for extra pumps as a result of large height differences in the system are two examples of aspects that influence the structure of a system. This means that when developing and expanding distribution networks, there is not one single solution that is optimal for all systems, instead individual solutions need to be developed and adapted for each system (Jakubek et al., 2023). System network models and simulations of temperatures, water flows and pressure drop, are thus potentially powerful tools to choose distribution techniques and design networks in order to achieve technically well-functioning and cost-efficient DH systems (Nguyen et al., 2020).

There are previous network-simulation studies that focus on the effects of reducing distribution losses by lowering the distribution temperatures. Pirouti et al. (Pirouti et al., 2013) have optimized flow and supply temperatures to minimize losses and total cost. Their results show that small pipe diameters, large pressure drops, and large differences in supply and return temperature in the system were advantageous. There are also studies focusing on developing simulation models for DH distribution. Valdimarsson (Valdimarsson, 2012) and Press (Press, 2022) for instance, use graph theory to present distribution losses, temperature drops, pressure drops, and flows for each individual pipe in a system. Jakubek et al. (Jakubek et al., 2023) simulates the losses for different types of pipes. Also, studies exist concerning low temperature DH distribution but without network simulations. Werner for example, investigated to what extent different types of distribution techniques for low-temperature DH have been implemented in real systems (Werner, 2022), unfortunately the article does not include an analysis of the losses associated to different distribution techniques.

1.1 Aim of the project

The overall aim of this project is to simulate a low-temperature DHS in order to investigate the impact of different distribution technologies on heat losses, distribution temperatures, and mass flows. A case study is made for the planned city district called Näringen in the Swedish city of Gävle. The district contains a high share of energy-efficient buildings and therefore illustrates the challenges that DHS will face in the future. The city district is divided into 11 sub-areas that that will be sequentially built. One of these areas were chosen for the distribution network simulations. For this area, a DH network is designed and implemented in a simulation model. The question to be answered in this project is:

How do different distribution system configurations for low-temperature district heating in the investigated area differ regarding distribution losses, distribution temperatures, and mass flow?

2 Background

This section gives a brief introduction to the 4^{th}-generation DH concept and a description of the district Näringen, which is the case study object in this study.

2.1 4^{th}-generation district heating

The 4^{th}-generation DH has several similarities with, what is known as the third generation of DH. Pressurized water is the heat carrier and the pipes are prefabricated and in the ground. The main difference between the two generations is the lower supply temperatures for the 4^{th}-generation. This primarily motivated by reduced distribution losses that comes with reduced temperature difference between the ground and the pipes. However, this also means that waste heat from low-temperature sources such as data centres, can be used to a further extent in DHSs (Tofani, 2022). Efficient DH distribution is generally considered a prerequisite for the future whit higher building energy efficiency (Lund et al., 2014). 4^{th}-generation DH is, however, still in the development stage and is currently best suited for newly built residential areas as existing networks are designed and adapted to existing and less energy efficient building stocks. Several low-temperature systems have been built in Germany, but a few projects in Sweden have also been tested. In order to integrate new low-temperature systems in new energy-efficient districts with the existing high-temperature systems, the new system can be connected to the main DHS as a sub-system using heat exchangers. This to enable control of pressure and temperatures in the sub-system separate from the main system (Borglund, 2020).

2.2 Näringen

The district of Näringen is centrally located in the Swedish city of Gävle and has a total area of 232 hectares. Gävle municipality has an agreement with Region Gävleborg and the Swedish government to transform Näringen into a sustainable city district containing 6,000 homes. In return, the Swedish government is planning investments for infrastructure worth of 20 billion SEK in Gävle until 2040 (Gävle kommun, 2021). A map of the district and the planned sub-areas are presented in Fig. 1. This paper focus on sub-area 11 that contains 69 buildings, of which 53 are residential and 16 commercial buildings. There is no DHS in this area today, the designed pipe network presented here is therefore a possible design for a future system.

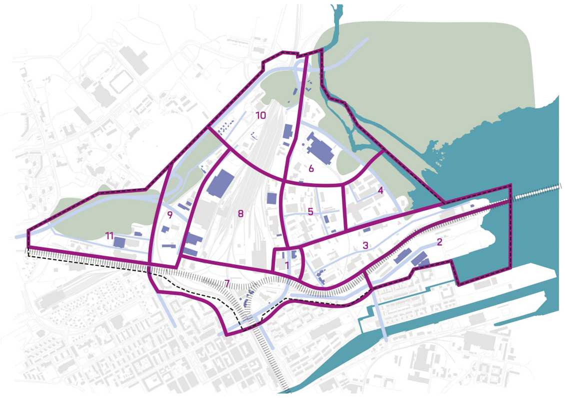


Figure 1. Overview of Näringen and the preliminary sub-area breakdown of the district.

3 Methodology

This section describes the process from designing the distribution systems in the sub-area and implementing it into the simulation tool.

3.1 Model description

The simulation tool used in the project is based on the Python programming language and created by Arvid Press (Press, 2022). The tool is further developed in this project to increase the precision of the calculations for heat losses and temperature drop. The two main changes were first, that the heat loss calculations was extended from only considering one single pipe above ground to instead consider two separate pipes in the ground. The second main improvement is an implementation of a minimum flow requirement in the system. The latter to illustrate a hot water circulation loop used to avoid extremely low water flows when space heating demand is low. The simulation tool is based on graph theory, which means that the DH system is implemented by defining all branches and connection points as nodes/points and all DH pipes as arcs/edges, and that the system components and its connections are described as a complete graph. A system can thus be described by a matrix where the rows correspond to the number of connections and the columns corresponds to the number of pipes. The elements in the matrix define the direction of the edges, 1 represents a start node, -1 an end node, and 0 that there is no connection between the nodes. This means that each column in the matrix can only have two nonzero elements, 1 and -1 , because each edge (DH pipe) must start and end somewhere. The matrix is therefore specific for every system, two examples of matrices and for further description of the mathematics behind the simulation tool are described in (Valdimarsson, 2012) and (Press, 2022). An illustration of a principal system as described in the simulation tool is presented in Fig. 2.

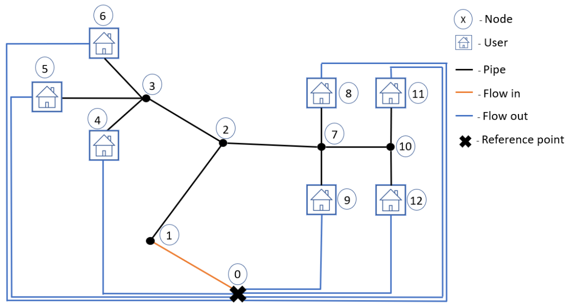


Figure 2. Example system illustrating the model principle.

3.2 *Distribution network design*

The distribution network in sub-area 11 is designed based on a map of the planned buildings and streets. The structure of the pipe network follows a tree-structure, thus there are no loops and only one inlet to the system. In addition to this, the inlet to the system is placed to limit the distance to the system's outermost connection point. The map was thereafter loaded into QGIS (GIS simulation program) and by using an integrated measuring tool, all pipe lengths could be determined and used to describe the system in the simulation tool.

One of the buildings in the area is excluded from the simulations since it is a parking garage and is assumed to not be heated. The layout of the distribution system and how it connects the buildings is illustrated in Fig. 3.

Figure 3. Distribution network in sub-area 11.

3.3 *Distribution techniques*

When distributing DH, the most commonly used technology is a 2-pipe system where the space heating and domestic hot water have the same supply and return pipes. This configuration works for both high and low distribution temperatures. In this project, a classic low-temperature system with a 60°C distribution temperature was simulated. The return temperature vary depending on the simulated building type. The supply temperature is restriced to a minimum of 60°C to avoid growth of legionella bacteria in the domestic hot water system (Fredriksen & Werner, 2014). A schematic view of the 2-pipe system can be seen in Fig. 4 where SH stands for ”space heating” and DHW stands for ”domestic hot water”.

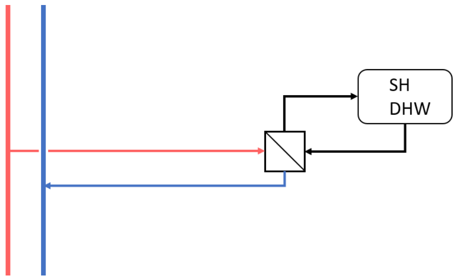


Figure 4. Pipe configuration 2-pipe system.

The second investigated distribution system configuration is a cascaded 3-pipe system, where the space heating supply pipe is connected to the main system's return pipe. The difference from from the above described 2-pipe system is that the space heating and domestic hot water supply is divided into two separate pipes. The 3-pipe configuration thus have the option of having different supply temperatures for the space heating and the domestic hot water, that the pipe for space heating can be disconnected during months without heat demand, and that each supply pipe can be individually sized for the respective heat demand. In a low-temperature network with energy-efficient buildings, the 3-pipe system provides the possibility of lowering the temperature of the supply pipe for space heating below the legionella requirement, which potentially reduces distribution losses and enables the utilization of more low-temperature residual heat. The supply temperature for SH depends on the temperature requirement in each building type. A schematic view of the cascade-connected 3-pipe system can be seen in Fig. 5.

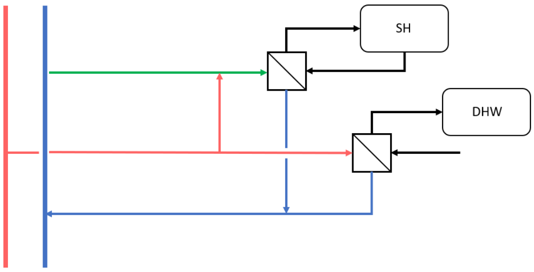


Figure 5. Pipe configuration of the cascade-connected 3-pipe system.

However, the 3-pipe systems need to have a back-up connection to the main systems supply pipe (or some other local high temperature source) to secure that the supply temperature during peak demand is sufficient and to ensure that the legionella requirement is met.

3.4 *Simulations*

This section describes the used formulas and parameters as well as how the simulations were executed.

3.4.1 *Dimensioning*

The first step was to size the pipes in the system (see Eq 1), which is done by calculating the system water flow demand using the design outdoor temperature (in Sweden known as DVUT) and the specific temperature demands of each building (Fredriksen & Werner, 2014). DVUT is defined as the average value of the outdoor temperature during the coldest day and is the temperature at which heating systems are dimensioned according to the Swedish national board of building, housing and planning building regulations (BBR) (Warfvinge & Dahlblom, 2010). Simulations are made with outdoor temperature data for 2022 provided by Gävle Energi AB, that owns the main district heating system in Gävle.

$$d_i = \left(\frac{8\lambda}{\pi^2 \rho P_{dl} \dot{m}_i^2} \right)^{\frac{1}{5}} \tag{1}$$

In Eq 1, P_{dl} is the pressure drop per meter and is assumed to be 200 pa/m, λ is the friction factor, ρ is the water density and $\dot{m}_i$ is the mass flow in each pipe. The calculations were done for both distribution system configurations and building types. The flow demand is used to calculate the pipe sizes and thereafter is the obtained pipe dimensions used to calculate the temperature drop in the system at DVUT. In addition to the pipe-sizing calculations, a simulation was also done over all hours of the year to calculate the total distribution losses. Calculations were made for both BBR buildings and passive houses, for detailed description of the building standards see (Israelsson, 2023).

3.4.2 *Distribution losses*

The distribution losses were simulated with hourly data using the equations for two insulated pipes in the ground, as described in chapter 5 pages 80-82 in (Fredriksen & Werner, 2014).

3.4.3 *Cascaded system*

In this part, calculations of return temperatures and flows for the cascaded 3-pipe system are presented. Mass flow and return temperature are calculated according to Eq. 2-5. T stands for temperature and $\dot{m}$ stands for mass flow. The indexing r,H represents return pipe of the main system, p,H represents the primary pipe of the main system and p,S represents the primary pipe in the secondary system. $\dot{m}_{tot,H}$ is the known total mass flow in the main system, see Tab. 1. The impact of the return temperature from the subsystem on the return temperature on the main system is calculated using a flow-weighted average value for the two temperatures.

$$T_{r,H}\dot{m}_{r,H} + T_{p,H}\dot{m}_{p,H} = T_{p,S}\dot{m}_S \tag{2}$$

$$\dot{m}_{r,H} = \dot{m}_S(1 - \frac{T_{p,S} - T_{r,H}}{T_{p,H} - T_{r,H}}) \tag{3}$$

$$\dot{m}_{p,H} = \dot{m}_S - \dot{m}_{r,H} \tag{4}$$

$$T_{ny,H} = \frac{(\dot{m}_{tot,H} - \dot{m}_{r,H})T_{r,H} + \dot{m}_S T_r}{\dot{m}_{tot,H}} \tag{5}$$

Eq. 3 determine the required flow from the main system's return pipe while required flow from the primary pipe is determined from Eq. 4. Eq. 5 calculates the new return temperature ($T_{ny,H}$) in the main system.

3.4.4 *Mass flow*

The mass flow at DVUT was simulated for the different building types. The required mass flow was compared to a traditional high-temperature system. Additionally, simulations for two different minimal flow levels a were performed to determine the impact of the heat circulation-loops on the distribution temperatures. The minimum mass flow was initially and iteratively set to 0.02 kg/s to avoid significant losses. Thereafter, a minimum flow of 0.1 kg/s was investigated as it is suggested by Alros (Alros, 2015).

3.4.5 General input data

Constants used in the calculations are presented in Tab. 1. Due to a lack of measured data for the specific site, the ground temperatures for heat loss and temperature drop calculations are illustrated by mean values of the outdoor air temperature for different parts of the year; December for the pipe sizing calculations, annual mean for distribution loss calculations, and the summer months (June, July, and August) when investigating the minimum flow requirements (Fredriksen & Werner, 2014).

4 Results

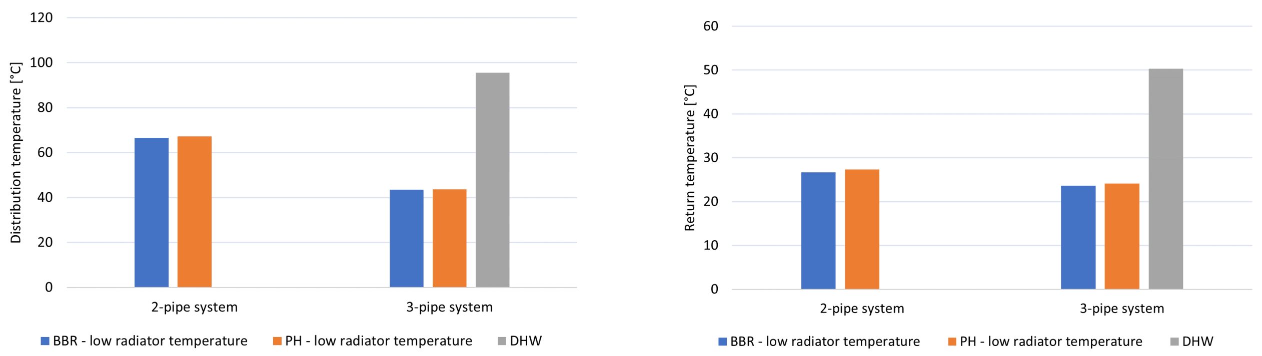
This section presents the results from the simulations. In the first part, distribution temperature, return temperature, and distribution losses for the different pipe systems and building types are presented. In the second part, results showing the impact of a cascaded system on the main system temperatures is presented. Finally, the mass flow results are presented.

Table 1. Constant parameters for the simulations.

Parameter	Value	Unit
$T_{a,DVUT}$	-3.1	$°C$
$T_{a,dist}$	8.6	$°C$
$T_{a,summer}$	19.3	$°C$
$T_{p,H}$	99.7	$°C$
$T_{r,H}$	49.3	$°C$
$\dot{m}_{tot,H}$	15.8	kg/s

4.1 Temperatures and distribution losses

The temperatures and distribution losses for the subsystem are presented in Fig. 6. The temperature requirement in Fig. 6a and the return temperature in Fig. 6b are simulated at DVUT. It can be deduced from the figures that low radiator temperature for both BBR buildings and passive houses when using 2-pipe systems give similar results. Using a 3-pipe system, the


(a) Distribution temperature for 2- and 3-pipe systems.

(b) Return temperature for 2- och 3-pipe systems.

(c) Distribution losses for 2- och 3-pipe systems.

(d) Relative distribution losses for 2- och 3-pipe systems.

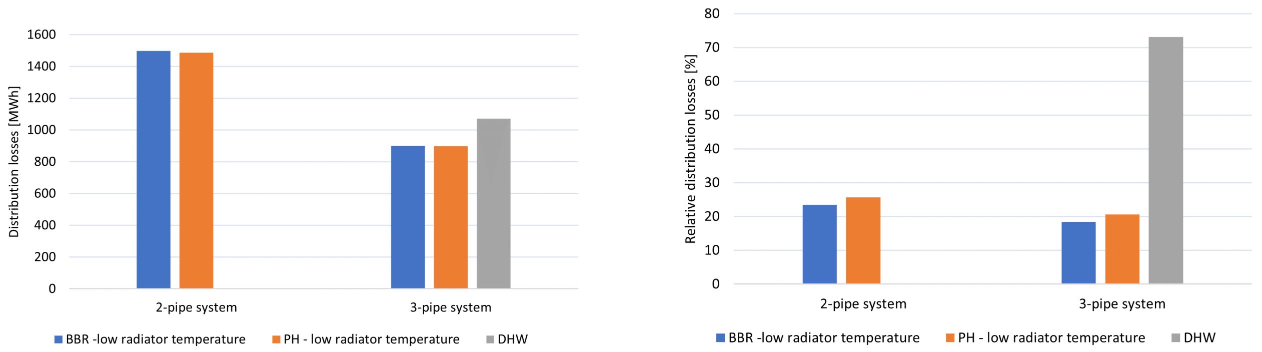


Figure 6. Distribution and return temperatures at DVUT and the annual absolute and relative distribution losses for buildings according to BBR and passive house standard in sub-area 11.

difference between BBR buildings and passive houses is small but there is a significant difference compared to the 2-pipe system. With a 3-pipe system, the temperature required for the domestic hot water is 96°C for the different building types since it only depends on the residents' hot water use (this is further explained in Section 5.1).

Fig. 6c and 6d shows absolute and relative distribution losses in the system. For the 2-pipe and 3-pipe systems, the difference in losses between the building types is small. The absolute distribution losses are lower for passive houses, while the relative distribution losses are lower for BBR buildings. The distribution losses for the domestic hot water account for a large proportion of the 3-pipe system and the total losses are greater than for the 2-pipe system for the different building types.

4.2 *Cascaded system*

The flows required from the main system pipes (return and primary) depending on the different building types, are presented in the two left stacks of bars in Fig 7. The right stack of bars presents the available flow in the main system pipes.

Fig. 7 shows that neither BBR buildings nor passive houses can be supplied with heat entirely from the main system's return pipe since the available mass flow (15.8kg/s) is not sufficient. This means that a little flow from the primary pipe must be used, even though the temperature requirement (see Fig. 6a) is lower than the return temperature in the main system (see Tab. 1).

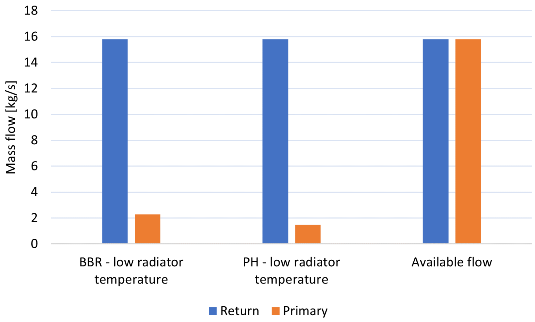


Figure 7. Mass flow requirements for the different building types in sub-area 11 when using a cascaded system.

The new return temperature for the sub system and the impact of the 3-pipe cascading system configuration on the return temperature in the main system is presented in Tab. 2. The results show that the greatest temperature reduction of the return in the main system is obtained with BBR buildings, which is explained by the higher flow requirements. For the sub-system, the new return temperature in the main system will be the same as the return temperature in the sub-system when the entire flow is used to supply the heat demand, see Fig. 6b.

Table 2. Temperature and temperature reduction in the main system return pipe for the different building types for sub-area 11.

	Return temperature [°C]	ΔT [°C]
BBR low temp. rad	23.6	25.7
PH low temp. rad	24.1	25.2

4.3 *Mass flow*

In this section, the results for the mass flow at DVUT for the low temperature systems compared to the mass flow at current standard radiator-temperatures levels are presented. The results from the analysis of the minimum flow requirements are also presented here.

4.3.1 *Flow requirement at DVUT*

Fig. 8 shows the flow demand for 2- and 3-pipe systems for the low-temperature radiators compared to current standard radiator-temperatures. The result shows that the flow requirement is lower with current temperature standards, when compared to the calculated temperatures for low-temperature radiators in (Israelsson, 2023). The largest flow is required for low-temperature radiators in BBR buildings, which is as expected due to the higher heat demand compared to passive houses.

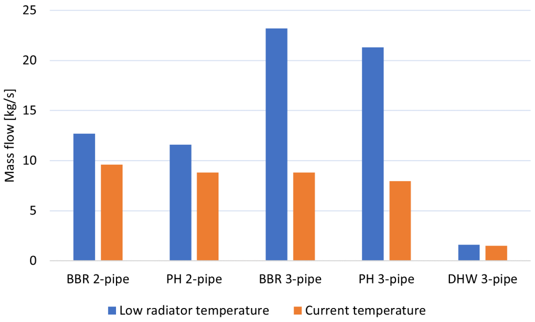


Figure 8. Flow demand with optimized temperature requirement and today's temperature for the different building types with 2- or 3-pipe distribution systems.

4.3.2 *Sensitivity analysis of the minimum flow*

When simulating the impact of the minimum flow on the temperature requirements and the total flow in the distribution system. This analysis is performed for the summer months when the heating demand is low and thus flow volumes in the system is generally small.

For higher heat demand periods the flow levels are significantly higher and heat circulation loops are thus not needed. The pipe sizes were obtained from the first part of the project when the system was sized for the heat demand at DVUT. As there is no need for space heating during summer, the 3-pipe system only uses the domestic hot water pipe in this case.

Tab. 3 presents the mass flow results that clearly shows that an increased minimum flow in the system reduces the temperature requirement in the subsystem, this goes for both 2- and 3-pipe systems. The mass flows, on the other hand, increases as a direct effect of the increased minimum flow.

Table 3. Distribution temperature and mass flow during the summer for sub-area 11 with different minimal flows.

	Dist. temp [°C]	Mass flow [kg/s]
2-pipe (0.02 kg/s)	105.8	1.6
2-pipe (0.1 kg/s)	67.8	6.8
3-pipe (0.02 kg/s)	84.6	1.6
3-pipe (0.1 kg/s)	64.5	6.8

5 Summary and Discussions

5.1 Results analysis

With the 3-pipe system, the temperature in the space heating pipe is lower when compared to the 2-pipe system. This, however, comes with low domestic hot water flows for the 3-pipe system (see Fig. 8), that cause large temperature drops in the system. This means that, in order to meet the temperature requirement of 60°C at the user, the temperature supplied to the systems needs to be as high as 90°C (see Fig. 6a). If the goal is to lower the temperature in the entire Gävle DH network and not only in Näringen, these results suggest that a 2-pipe system is better since the supply temperatures does not exceed 70°C for this system configuration.

The absolute distribution losses are marginally lower for passive houses compared to BBR buildings which is explained by the reduced heat demand in passive houses. The reason to why low-energy buildings with low radiator temperature requirements yield high distribution losses is because of relatively high flow requirements at DVUT (see Fig. 8). This high flow demand yield large pipe diameters, which means that the low flow volumes in summer leads low flow rates, high temperature drops, and in the end increased losses. The combined losses for space heating and domestic hot water for 3-pipe systems result in the total distribution losses being higher for both BBR buildings and passive houses. It is explained by the fact that the low flows for domestic hot water lead to large losses.

Analysis of the relative distribution losses in Fig. 6d shows that the lower absolute distribution losses for passive houses is combined with a relatively larger reduction of the heat demand, leading to increased relative losses for the system. Again, the problem with the domestic hot water supply in the 3-pipe systems is clear, the relative losses exceed 70% in sub-area 11, which in combination with the high-temperature requirements means that such a system design is not well suited for Näringen.

The results for the cascaded systems show that the mass flow in the main system return pipe is limited, but that it could supply at least parts of the heat demand in Näringen. A cascaded system in parts of Näringen may, however, cause problems in the future if the return temperature in the main system is reduced due to other efficiency measures. In that case, the potential for heat supply from the return pipe to Näringen would be further limited. Also, an investigation regarding the need for circulation pumps to maintain the pressure in the system is needed.

5.2 Summary

A model based on graph theory has been shown to be an effective tool when simulating DH networks. Designing and implementing future systems is possible if access to data on the heat demand, geographic location, and temperature requirements for the heating systems is available.

When using low-temperature DH for both space heating and domestic hot water, 2-pipe systems were shown to yield the lowest total distribution losses and distribution temperature requirements. 3-pipe systems have the potential to reduce distribution losses for space heating, but the low domestic hot water flows mean that the total losses and the temperature required in the system increase.

Finally, it is concluded that cascading entire or larger parts of Näringen to the return pipe of the nearby branch of the main network is not possible as the flow demand exceeds the available flow.

Acknowledgement

This work was supported by the Swedish Energy Agency, project Samspel mellan värme, kyla och elanvändning i ett bostadsområde med en hög andel solcellsproducerad el [grant number P2022-00442].

6 Nomenclature

DH	District heating
DHS	District heating system
SH	Space heating
DHW	Domestic hot water
BBR	Boverkets building regulations
PH	Passive house
DVUT	Design outdoor temperature

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