IMPROVED SUPPLY OF DISTRICT HEAT TO HYDRONIC SPACE HEATING SYSTEMS

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 Improved supply of district heat to hydronic space heating systems

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Concerning the reliability of district heat supplies, the present work has led to new knowledge regarding the dependence of the district heating technology on electricity. A substantial heat supply can be maintained in numerous buildings in case of an electric power failure since natural circulation can be expected to take place in the heating systems. A turbine-driven circulation pump has the potential to further reduce the dependence on electricity.

Concerning a low return temperature from consumer substations, which is a key performance measure for district heating substations, a new method for the control of the heating system has demonstrated a potential of reducing the district heating return temperature. The method involves the control of both the supply temperature and the flow rate in the heating system. The possibility of achieving a low return temperature from different connection schemes of the substation has also been studied.

Key words: District heating, hydronic space heating, natural circulation, low return temperature

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My family: mother, father and brother, and the most important person to me: my wife Sofi, for your support!
List of publications

This thesis is based on the following papers, referred to in the text by their Roman numerals. The papers are appended at the end of the thesis. Please note that I changed my name in 2008, from Ljunggren to Lauenburg.

Paper I  Optimised space heating system operation with the aim of lowering the primary return temperature
Ljunggren, P., Johansson, P.-O., Wollerstrand, J.

Paper II  Obstacles for natural circulation in heating systems, connected to district heating via heat exchangers, during a power failure
Johansson, P.-O., Ljunggren, P., Wollerstrand, J.

Paper III  Modelling space heating systems connected to district heating in case of electric power failure
Lauenburg, P., Johansson, P.-O., Wollerstrand, J.
Conference proceedings from Building Simulation 2009 (11th International Building Performance Simulation Association Conference and Exhibition), Glasgow, UK.

Paper IV  A turbine-driven circulation pump in a district heating substation
Wollerstrand, J., Lauenburg, P., Frederiksen, S.
Conference proceedings from ECOS 2009 (22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems), Foz do Iguaçu, Brazil.

Paper V  Improved cooling of district heating water in substations by using alternative connection schemes
Johansson, P.-O., Lauenburg, P., Wollerstrand, J.
Conference proceedings from ECOS 2009 (22nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems), Foz do Iguaçu, Brazil.
Paper VI  District heating in case of power failure
Lauenburg, P., Johansson, P.-O., Wollerstrand, J.

Paper VII  Adaptive control of radiator systems for a lowest possible
district heating return temperature
Lauenburg, P., Wollerstrand, J.
Submitted for publication (2009).
My contributions to the publications

**Paper I**  I performed the calculations and wrote the paper together with Per-Olof Johansson and Janusz Wollerstrand. Janusz also performed the field experiment.

**Paper II**  I performed the field studies, the calculations and wrote the paper together with Per-Olof Johansson with guidance from Janusz Wollerstrand.

**Paper III**  I performed the simulations and wrote the paper together with Per-Olof Johansson with guidance from Janusz Wollerstrand.

**Paper IV**  The concept and the prototype were developed by Janusz Wollerstrand and Svend Frederiksen. I performed the experiments and wrote the paper together with Janusz.

**Paper V**  I wrote the paper together with Per-Olof Johansson. Per-Olof performed most of the simulations with assistance from me and Janusz Wollerstrand.

**Paper VI**  I performed the field experiments and the simulations together with Per-Olof Johansson. Janusz Wollerstrand assisted us. I wrote the paper.

**Paper VII**  I performed the calculations and developed the control algorithm together with Janusz Wollerstrand. I wrote most of the paper.
Other related publications by the author:

Cascading in District Heating Substations – in Pursuit of Low Return Temperatures
Ljunggren, P., Wollerstrand, J., Frederiksen, S.
Conference proceeding from the 9th International Symposium on District Heating and Cooling, 2004, Espoo, Finland.

Optimal och robust drift av fjärrvärmeentraler – avkylning och egenskaper vid elavbrott (Optimal and robust operation of district heating substations – cooling and conditions during a power failure)
Ljunggren, P.

District heating supplies during a power failure
Ljunggren, P.

Fjärrvärme vid elavbrott – slutrapport (District heating in case of power failure – final report)
Lauenburg, P., Johansson, P.-O.
Project Report, Department of Energy Sciences, Lund University, Faculty of Engineering, 2008.

Fjärrvärme vid elavbrott (District heating in case of power failure)
Lauenburg, P.

Fältförsök med adaptiv reglering av radiatorsystem (Field experiments with adaptive control of radiator systems)
Wollerstrand, J., Lauenburg, P.
POPULÄRVETENSKAPLIG SAMMANFATTNING

I ett fjärrvärmesystem produceras varmvatten centralt och distribueras till användare via ett rörnät. Fjärrvärme innebär att man kan uppnå bättre rökgasrening, att man inte är bunden till ett visst energislag och att det är möjligt att använda energi som annars skulle gå till spillo, t ex restvärme från en industri eller från elproduktion. Ett enkelt, bränsleeldat kraftverk kan bara omvandla en begränsad del av den tillförda energin till el medan huvuddelen normalt kyls bort. I ett s.k. kraftvärmeverk tillvaratas däremot restvärmen och distribueras i ett fjärrvärmenät.

Fjärrvärmen är väl utbyggd i Sverige och svarar för 90 % av uppvärmningen av våra flerbostadshus. År 1980 stod olja för 90 % av den tillförda energin till den svenska fjärrvärmen medan biobränsle och restvärme idag står för 76 %. Internationellt har fjärrvärmen betydande marknadsandelar främst i de skandinaviska länderna och i en del länder i centrala och östra Europa. Fjärrvärme förekommer i mindre utsträckning i andra länder, bland annat i USA. Idag svarar fjärrvärme för 6 % av uppvärmningen i Europa men är under uppgång. Möjligheterna är oerhörda med tanke på att värmeförlusterna i den europeiska energibalansen (som främst uppstår i bränsleeldade kraftverk) är större än slutanvändningen av värme.

Ett fjärrvärmesystem består av flera olika delar: produktion, distribution och användare. Värme överförs till byggnaden i fjärrvärmecentralen.

Angående tillförlitlighet har möjligheterna att leverera fjärrvärme vid ett långvarigt elavbrott studerats. Det visade sig att det finns goda möjligheter till självcirkulation i de anslutna värmesystemen, vilket uppstår då det finns en tillräckligt stor temperaturskillnad mellan fram- och returledningen i ett värmesystem eftersom varmt vatten väger mindre än kallt. Om det finns reservkraft för att upprätthålla produktion och distribution av fjärrvärme kan värme överföras till byggnaden trots att cirkulationspumpen i fjärrvärmecentralen i byggnaden slutar att fungera. Resultaten visar att de allra flesta byggnader kan få betydande självcirkulation vid ett elavbrott, vilket innebär att man normalt klarar flera dygn innan en eventuell evakuering blir nödvändig.

För att minimera effekten av ett omfattande elavbrott pågår arbete för att under ett avbrott kunna etablera ett mindre elnät genom att utnyttja lokal elproduktion. För ett kraftvärmeverk är det ofta en förutsättning att restvärme från elproduktionen kan tas emot av fjärrvärmennätet. Det var tidigare oklart huruvida detta var möjligt vid ett elavbrott, men har nu alltså visat sig vara det.

God avkylning, d v s en så stor temperaturskillnad mellan fram- och returledning som möjligt, har varit ett ständigt aktuellt tema inom fjärrvärme forskningen. På så sätt behöver mindre vatten pumpas runt, vilket sparar energi och frigör kapacitet i nätet. En låg returtemperatur gynnar dessutom verkningsgraden i vissa typer av produktionsanläggningar, t ex pannor med rökgaskondenserings. God avkylning kan även ge möjlighet till en sänkt framledningstemperatur vilket innebär en positiv effekt för kraftvärmeverk som då kan producera mer el och för restvärme som kan utnyttjas bättre. Sänkta temperaturer i fjärrvärmennätet minskar också värmeförlusterna från rören.

Med syfte att förbättra avkylningen har en metod för bättre reglering av värmesystem utvecklats. För varje utetemperatur bestäms den kombination av framledningstemperatur och flöde i värmesystemet som ger bästa möjliga avkylning av fjärrvärmevattnet.
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INTRODUCTION

Background

District heating involves the production of hot water in one or more production facilities as well as the distribution to end users via a piping network. This is contrary to local heat generation in which each user has its own heat source. Producing heat in few, but large, production units can provide benefits such as less pollution and a higher efficiency. Another advantage is that the district heating technology is not tied to a particular energy source, which renders it possible to use energy that would otherwise be wasted. District heating is in many countries intimately linked with cogeneration, i.e., the generation of electricity during which the residual heat is procured and distributed via a district heating network, thus providing an efficient use of energy resources.

District heating can be considered a mature technology. However, there are obviously many areas that can be developed and improved in numerous ways. District heating research is conducted within a variety of disciplines: economy, politics and technology, and concerns the marketing, expansion and efficiency of district heating systems. This, in turn, involves the production, distribution and use of district heat. The studies presented in this thesis concern hydronic space heating systems connected via heat exchangers, so-called indirect connection, to a district heating network with the objective of improving the reliability of district heat supplies and lowering the return temperature from consumer substations.

Concerning the reliability of a district heat supply, the performed work has led to new knowledge regarding the dependence of the district heating technology on electricity. Regarding a low return temperature from consumer substations, which is a key performance measure for district heating substations, a new method for controlling the heating system has demonstrated a potential to reduce the district heating return temperature. The possibility of achieving a low return temperature from innovative connection schemes of the substation has also been studied.
When designing a substation, one can choose between indirect and direct connections of the hydronic heating systems, i.e., there can be a heat exchanger providing hydraulic separation between the primary (district heating) and secondary (building-internal) water flows, or not. In Sweden, and certain other countries, the indirect connection predominates. Both methods naturally have their pros and cons. For the work presented in this thesis, an indirect connection has been assumed and two of its disadvantages have been addressed: the thermodynamic loss and the local dependency on electricity involved during the use of a heat exchanger.

The results presented herein show that the influence of these disadvantages can be reduced by employing variants of so-called low-flow processes in hydronic heating systems.

Objectives
The objective of the studies have been to investigate and present new aspects of what is generally termed low-flow hydronic heating systems – connected to district heating networks – in terms of reliability and a low return temperature of the district heating water. The intention of the work has thus also been to minimise some of the disadvantages of an indirect connection of the hydronic heating system, i.e., the thermodynamic loss, as well as improving the reliability of the heating systems in terms of dependency on electricity.

Thus, reliability here refers to exploring the possibilities for heat supply in district heating systems in the event of a major power failure, by the very low radiator flows that can occur through natural circulation in hydronic heating systems. The studies related to this matter are presented in Paper II, Paper III, Paper IV and Paper VI.

A low return temperature of the district heating water signifies exploring the possibility of achieving the lowest possible primary return temperature for a given primary supply temperature, which will often lead to a reduced use of primary energy resources. In the study presented in Paper V, various alternative connection schemes for district heating substations and their impact on the return temperature were studied. Paper I and Paper VII present a new control algorithm for the hydronic heating system. The control method employs an optimal combination of supply temperature and a low, variable flow in the hydronic heating system, in order to achieve the lowest possible return temperature.
Figure 1 illustrates the objective of the studies.

Based on previous work within the area, both Swedish and international, the studies were carried out with the support from computer simulations and practical experiments in several different buildings.

**Limitations**

As already mentioned, the major limitations of the work are that indirect connection of heating systems to the district heating network and the use of instantaneous water heaters were assumed. Furthermore, no economic evaluation of the attained results was performed.

**Outline of the thesis**

The first part of the thesis presents an overview of some areas of district heating technology that are relevant for the studies described in the papers. The intention has been, based on a summary of what has in general been done in recent years, to point out how the work presented in this thesis has contributed to the development. The second part of the thesis consists of the papers.

The next chapter provides some relevant background information on the district heating concept in general, the various parts of the system and the difference between a direct and indirect connection of heating systems. This is
followed by a chapter on internal systems of buildings, mainly regarding space heating, with focus on those aspects that are relevant to the studies presented in the papers. The chapter includes a brief overview of some innovations within the field during the past few years.

The next chapter is devoted to the importance of low temperatures in district heating systems and the parameters affecting it. Subsequently, the reliability of district heating, with emphasis on the dependency on electricity in district heating systems, is presented.

This is followed by a brief chapter on methods and by some concluding reflections and comments on future studies. The papers are appended at the end of the thesis.
OVERVIEW OF DISTRICT HEATING

This chapter aims at providing relevant background information regarding district heating technology. When no specific references are provided, the presented information can be considered to be common knowledge with regard to district heating, which, among other, has been described in detail in a Swedish textbook by Frederiksen and Werner [21].

Fundamentals of district heating

Certain benefits of district heating have already been mentioned in the introduction, e.g., the fact that it provides a generally high efficiency in terms of utilisation of supplied primary energy resources. Low exergy resources, such as residual heat from power generation, industrial processes, waste incineration, solar and geothermal resources, which may otherwise be lost or difficult to utilise, can be transferred to a variety of consumers by means of a district heating system.

In buildings connected to district heating, the district heating water is used primarily for space heating and domestic hot service water. Other purposes include for example drying circuits, refrigeration and industrial applications. The district heating water can be used directly in the internal systems of the building, or its heat can be transferred to the internal systems of a building via heat exchangers.

District heating is common in Sweden with a market share of 90 percent for heating and hot water in multi-dwelling buildings. Non-dwelling premises also use district heat to a large extent while the share among single-dwellings is rather low. Altogether, district heating accounts for 54 percent of the energy used for space heating and domestic hot water in Sweden. [68] In 1980, oil accounted for 90 percent of the energy supply to district heating in Sweden. Today, bio fuels, waste, peat and waste heat account for 76 percent [67]. District heating has thus clearly contributed to a shift from oil in the Swedish building sector.
Internationally, countries with significant market shares of district heating are mainly found in Scandinavia and Eastern Europe. Nevertheless, district heating networks are found in many cities in certain countries in Western Europe and in the U.S.. The largest total volumes of district heat are found in Russia and Germany. The total market share in Europe amounts to only 6 percent, but is increasing. The potential is enormous, considering that the heat losses in the European energy balance (which mainly occur in fuel-fired power plants) are greater than the end use of heat. There is also a great potential to save energy through district heat-supplied refrigeration and district cooling (central production of cold water), considering a sharp increase in the demand for comfort cooling, which today is primarily based on electricity-consuming vapour-compression refrigeration. District cooling is increasing both in Sweden and internationally. The data in this paragraph are taken from the Ecoheatcool project [14].

One advantage of district heating, which is often highlighted, is the ability to use energy that is difficult to utilise or would otherwise be lost, such as residual heat or low-grade heat. A centralised production also provides better opportunities for efficient combustion and flue gas treatment. Werner [77] has estimated that district heating and cogeneration reduces the world’s carbon dioxide emissions from combustion by 3-4 percent, despite a market share of 3.5 percent of the world energy use. A disadvantage with regard to district heating is its relatively high investment cost, especially in built-up areas.

Production

There are several ways to produce district heat. For heat production only, heat-only-boilers can be used. In Sweden, heat-only-boilers currently account for the largest share of the district heat production [62]. As mentioned above, the supply of fuel has changed from mainly oil to wood fuels [67]. Today, boilers are usually equipped with flue gas condensers, which greatly increase their efficiency.

Cogeneration, or combined heat and power (CHP), technology is often mentioned in connection with district heating. It involves the simultaneous production of electricity and heat. All thermal power generation is associated with large heat losses that are difficult to utilise without a district heating network. Cogeneration can be considered as the employment of waste heat, even if the production of electricity is slightly decreased when the waste heat is utilised in a district heating network.
Another form of waste heat in district heating production is obtained from industrial waste heat. Other forms, such as waste heat from sewage treatment plants, however, require an increase of the temperature to match the district heating network level. Heat production from waste incineration, geothermal and solar heat also reduces the input of primary energy resources.

Typically, there is a mix of different production units in a district heating system. The operation of the units is usually based on the principle that the unit with the lowest operational cost is used for base load and the one with the highest operational cost is used for peak load. For example, a waste incineration plant may be used for base load and an oil boiler may be used for peak load.

There is often heat storage in connection with production units, in order to level out and optimise the heat production, generally on a shorter (daily) basis but sometimes also on a longer (seasonal) basis. For example, the power-to-heat ratio in cogeneration plants can be increased if the heat production is not required to be fully adjusted to match the current heat demand.

**Distribution**

Energy is distributed from the production units to the users through a piping system, where water is normally used as the heat carrier. There still exist some district heating systems where steam is used as the heat carrier, primarily in the U.S.

The heat supply in a district heating network is regulated by control of the differential pressure (the flow) or the supply temperature. Normally, both are used in order to obtain a high system efficiency, i.e., a low return temperature and moderate flows. In order to handle expected load changes, the network can also be charged with heat energy.

Temperature levels vary in different countries and even between district heating networks. In Russia, higher supply temperatures have generally been adopted (140-170°C), which is also the case in Germany (110-160°C). In Sweden, on the other hand, lower temperatures (100-120°C) prevail, and in Denmark, an even lower temperature level (around 80-90°C) is often used. [21] [63] [85]
**Substations**

In the district heating-connected buildings, there is generally some kind of substation where the energy is transferred from the district heating network to the internal systems of the building. There is also often charge measurement in the substation. District heating substations can be designed in a variety of ways, often according to different codes and to the traditions of various countries. A distinction may, for instance, be made between direct and indirect connection of the hydronic heating system. The latter involves a heat exchanger providing hydraulic separation between the district heating network and the heating system. With direct connection, the water circulating in the district heating network enters the heating system. Similarly, the domestic hot water system can be of either the open type, where tapping of hot water in the building signifies that water from the district heating network is drawn off, or of the closed type, which is more common, were a water heater is used.

**Direct vs. indirect connection**

The adoption of district heating is unevenly distributed in the world, which is likely to be a major contributing factor to the fact that the technology is characterised to a significant extent by national standards. The present work has been focused on the indirect district heating connection of heating systems due to it being the prevailing choice in Sweden, and not because it is necessarily the better choice in all respects.

There are advantages and disadvantages of both methods. A drawback with regard to a direct connection includes the risk of a leak in the heating system having large consequences and that it can be difficult to handle large pressure variations in networks with significant differences in height. In addition, there are risks involved from the fact that the supply temperature is generally high in the district heating network in order to meet the needs of all customers in the system. Unless the district heating network keeps a sufficiently low pressure and temperature level, it must be reduced to match the internal systems of a building. Directly connected district heating substations are often equipped with a shunt connection, where re-circulated water is admixed with the incoming supply water in order to reduce the temperature, and a throttling valve in order to reduce the differential pressure. Sometimes a jet (ejector) pump is used, which can reduce both the temperature and pressure.

In many countries, e.g., in Denmark and in Germany, both direct and indirect connections are employed, whereas the direct connection is the predominant choice in countries in Central and Eastern Europe.
The most common objection to the indirect connection is that the use of heat exchangers entails a thermodynamic loss, as a result of the return temperature from a heat exchanger always being higher than the incoming return temperature. Those who speak in favour of indirect connections claim, however, that the temperature difference in the cold end of the heat exchanger, sometimes referred to as grädigkeit, can be kept low with the use of modern plate heat exchangers. As the studies presented in Paper I and Paper VII try to demonstrate, the grädigkeit can be further reduced if the heating system control takes the heat exchanger characteristics into account.

The use of heat exchangers also involves a higher cost, although, it is not evident that the total cost of the installation is always required to be higher, considering that the primary temperature and differential pressure may need to be adjusted to the level of the secondary systems [21]. A third objection that can be raised against an indirect connection is its dependency on electricity. Direct connections do not automatically mean that district heating customers will be supplied with heat in the event of a power failure; three-way valves and controlled jet pumps will sometimes automatically close for safety reasons, i.e., to avoid extremely hot water entering the secondary systems, and the use of pumps in secondary systems may be necessary to ensure a proper function.

However, there is a natural potential to supply customers with district heat with a direct connection, provided that the production and distribution of heat can be maintained. With an indirect connection, the heat exchanger constitutes a barrier, which may seem impossible to cross, for the transfer of heat from the district heating network to the heating system. After studying several different buildings, as presented in, e.g., Paper VI, it could, however, be concluded that natural circulation has a notable potential for transferring heat, despite the use of heat exchangers.

**Connection schemes**

Connection schemes are another way of categorising district heating substations. When an indirect connection is adapted, it is not uncommon to use some kind of cascading of the different heat exchangers. The objective is to utilise the various temperature levels in different secondary systems so as to lower the return temperature of the district heating water. References [21] and [59] give detailed presentations of several kinds of connection schemes.

The most common type of cascading configuration is the two-stage connection scheme, where district heating water from the radiator heat exchanger is used to preheat incoming cold water intended for hot water
provision. This has been motivated by the rather high heating system temperatures, which have traditionally been employed in combination with an extensive use of hot water. Examples of other connection schemes include a three-stage configuration that exists in different variants: one commonly used in some parts of Sweden and another utilised in Russia. Moreover, a serial connection scheme has been employed in certain countries in Central and Eastern Europe.

Today, the parallel (one-stage) connection scheme is often preferred in Sweden (at least), due to it being simple, cheap and generally providing a return temperature that is comparable to the two-stage connection scheme [15]. Paper V shows examples of how cascading can be advantageous when heating system temperatures are low. Cascading involving hot water provision before (i.e., at higher temperature level) the heating system heat exchanger has proven to be beneficial, especially in buildings with a low usage of domestic hot water (e.g., non-residential). This is due to the relatively high return temperature of re-circulated domestic hot water being utilised.

It also deserves mentioning that there exist numerous variants of connection schemes for combinations of district heating and other heat sources, e.g., heat pumps and solar heating.
The two main services provided for by district heating, particularly in the case of dwellings, are the provision of domestic hot water and space heating. Other purposes, such as drying of clothes in bathrooms and washing facilities, refrigeration and industrial applications, are not addressed here. Domestic hot water and space heating systems are of course not specific for district heating but can be found in all types of buildings, regardless of the heating source. The design and operation of the systems have, however, sometimes been affected in various ways depending on if they are connected to district heating. This is especially the case in Sweden, where a large part of the multi-dwelling building stock is connected to district heating. One example is the need for a heating system providing a low return temperature of the district heating water. This also applies to, for instance buildings served by heat pumps, while boilers traditionally have demanded relatively high return temperatures.

**Domestic hot water**

When a closed domestic hot water system exists, the provision of hot water can be done either in heaters with accumulation or with heat exchangers (instantaneous water heaters). As for the distinction between a direct and indirect connection, there are advantages and drawbacks of both methods. For example, accumulation involves the use of smaller dimensions for district heating pipes and valves while instantaneous heaters generally provide lower return temperatures. Once again, practices have differed between countries. In Sweden, today, instantaneous heaters prevail, and this type of hot water provision has been assumed for the study described in Paper V, which deals with connection schemes.

**Space heating**

Space heating is often provided for by radiator systems, especially in countries with cold climates or with a large share of district heating. Underfloor heating, which has gained significant popularity in later years, is usually hydronic, as are radiator systems. Although steam was commonly used as a heat carrier
many years ago, radiator systems are nowadays normally water-borne. Ventilation systems are sometimes also used for space heating, causing the heat to be air-borne. In residential buildings, radiator systems are the most common (in Sweden, at least), while air-borne heat is often found in non-residential buildings, sometimes in combination with a radiator system. In the latter case, heat supplied by the air typically covers the heat losses from ventilation while the radiator system covers the heat losses from transmission. Paper II and Paper VI address heating systems with both radiators and ventilation, whereas the remaining papers deal with heating systems with exclusively radiators.

Radiator systems are typically designed as one- or two-pipe systems. One-pipe systems were relatively commonly adopted in the 1960s and 1970s, however, two-pipe systems are the overall predominant choice today. One-pipe systems have the advantage of somewhat lower installation costs, but are generally considered to be difficult to maintain and balance. [21]

**Heating system control**

There exist various ways to control the heat output in a heating system. Such methods can be based on a constant supply temperature combined with local flow control, or a constant flow rate in combination with a supply temperature curve, or both. Control of the flow, or of the supply temperature, can be based on the feedback (e.g., indoor temperature) and/or the feedforward (e.g., outdoor temperature) control principle. Here, we have dealt with the prevailing control method used in Sweden [13]; an outdoor temperature-compensated supply temperature (i.e., feedforward), ensuring that an adequate amount of heat is supplied to the building at each outdoor temperature.

Usually, the control curve for the radiator supply temperature is such that the temperature varies slightly non-linearly with the outdoor temperature, i.e., the curve is slightly bent due to heat transfer from the radiators increasing at high radiator surface temperatures. The feedforward signal (outdoor temperature) to the controller is nowadays usually dampened to compensate for the buildings thermal inertia: the indoor temperature does not instantly change when the outdoor temperature changes, and can in certain cases be supplemented by, for instance, a correction for the wind speed. The radiators are normally equipped with thermostatic radiator valves, of which the main task is to compensate for free heat (e.g., solar radiation, electrical equipment or body warmth) by reducing the flow through the radiator.
In Küçüka [32], the return temperature from a heating system controlled solely by outdoor temperature-compensation or exclusively by thermostatic radiator valves, respectively, was compared. The comparison was made with regard to direct and indirect connections. The conclusion was that a variable flow provides a lower return temperature. However, it is often pointed out that it is difficult to obtain a good control of the indoor temperature solely with thermostatic radiator valves. In Britain, where such regulation is widespread, a study has revealed that 65 percent of thermostatic radiator valves perform very poorly [36].

It should also be mentioned that radiator systems have a certain degree of self-regulation [76]. If the room temperature rises, e.g., due to solar radiation, the heat emission from the radiators becomes reduced.

Sometimes, the heating system control includes night setback, the purpose of which is to reduce the heat consumption during night time, accomplished by lowering the supply temperature in the radiator system. However, the method is debated, because many buildings have a significant inertia and the benefit of night setback is considered to be small, and may also be the result of thermostatic radiator valves that tend to open. Night setback has sometimes been accompanied by a morning boost, which means that after the night setback period, in order to recover the desired indoor temperature, the supply temperature in the radiator system is increased. For district heating connections, however, this may cause significant district heat flow peaks and high return temperatures. [21]

The breakthrough of variable speed pumps deserves to be mentioned in connection with the control of hydronic heating systems. Today, these may be regarded as state-of-the-art equipment and have greatly improved the working conditions of thermostatic radiator valves [15]. The control method described in Paper VII uses speed control to optimise the thermal performance of the system.

**System temperatures**

Regarding radiator system temperatures, as well as district heating network temperatures, different levels prevail - both between countries but also depending on the age of the systems. The general ambition has been to lower the temperatures, since these are the single largest factors determining the temperature levels in the district heating networks [21]. Skagestad and Mildenstein [58] gives some examples of typical design radiator temperatures (supply/return temperatures) in various countries:
Denmark   70/40°C  
Finland    70/40°C  
Korea      70/50°C  
Romania    95/75°C  
Russia     95/75°C  
United Kingdom  82/70°C  
Poland     85/71°C  
Germany    80/60°C  

The development in Sweden clearly shows how lower radiator temperatures are strived for. Previously, higher temperatures such as 90/70°C and 80/60°C have been used, partly because there were no incentives for low temperatures in systems with boilers, but also because smaller radiators could be employed. The advantages of low temperatures have led to lower temperatures being used today, e.g., 60/45°C, 60/40°C or 55/45°C. Since 1982, temperatures higher than 55°C (60°C in certain cases with district heating) are not allowed in new heating systems, which should promote the use of low-temperature heating systems, e.g., solar heating [21]. Underfloor heating systems have become more frequent and contribute to even lower temperatures.

One factor affecting the radiator temperatures in practice is the degree of oversizing of the heating system. There is a substantial oversizing of the radiator system in general and of the radiator surfaces in particular, as presented in both Swedish [26], [71] and international studies [36], [46] and [58]. This is due to an overestimation of a building's heat losses, which also often tend to decrease over time by energy-saving measures. Another reason is that, during the design stage, the components are generally selected in sizes larger than required to ensure safety margins. In order for oversizing not to cause overheating of a building, the supply temperature or the circulation flow in the radiator system must be adjusted. As described in Paper VII, the control curves of the various substations in an area were found to differ to a surprisingly large degree, despite the fact that the houses were built at the same time and were of similar structure. Similar experiences have been described by Lindqvist and Walletun [37].

The most common approach is to reduce the supply temperature in an oversized radiator system to avoid that indoor temperatures become too high. However, the flow can also be reduced and the system can be adjusted to work as a so-called low-flow system. By substantially reducing the flow while maintaining a high supply temperature, a low return temperature can be achieved. Although the heat transfer in the heat exchanger is deteriorated, a
lower district heating return temperature is generally obtained [15]. To intentionally install larger radiators in order to obtain a low-flow system is rarely economically viable [5]. On the other hand, oversizing and the design of systems for a high flow and a small temperature difference often render it possible to adapt the low-flow method.

Early studies on low-flow systems were made by Schelosky [54] and Amberg [1]. The latter showed that an economic comparison of different temperature programs spoke in favour of low-flow systems. The studies presented in these articles paid much attention to the function of the thermostatic radiator valves, which was investigated further in [55] and [56]. The studies were in fact based on a direct district heating connection and a high district heating supply temperature entering the radiator system, which resulted in very low flows and therefore high demands on the thermostatic radiator valve function. Wasilewski [75] proposed low-flow systems in Poland but called for improved opportunities for the control of the radiators. In Sweden, the first experiments with low-flow systems, sometimes termed the “Kiruna method” (after the town where the experiments took place), were presented in [2]. Today, the method is used to a certain extent, although there still seems to be a division between those who advocate for it and its opponents. Trüschel, who conducted a comprehensive study on hydronic heating systems, means that the return temperature is lowest and thermostatic radiator valves are the most effective in a low-flow system [71]. The low flow leads to very low pressure drops in the system and all thermostatic radiator valves thus work at approximately the same differential pressure and with a high authority. The low district heating return temperature of low-flow systems has also been demonstrated by, among others, Gummérus and Petersson [26], Petersson [48] and Petersson and Werner [49]. Moreover, all these authors stressed the importance of the systems being balanced since this has the greatest impact on the district heating return temperature.

One drawback of the method that is usually pointed out is the fact that it is more sensitive to abnormalities in the systems (such as hydraulic short circuits and malfunctioning thermostatic radiator valves). However, such deviations are not the result of the choice of the balancing method; the low-flow system can in fact be seen as being more able to clarify malfunctions instead of “hiding” them. Another drawback may be that a reduction in the district heating supply temperature can result in an increased district heating return temperature due to an increased flow if the difference between primary and secondary supply temperatures is small [21]. This is most critical around the so-called supply temperature breakpoint, typically between 0-5°C outside air.
temperature, where the supply temperature has not yet been raised, although
the heat load is relatively high. [ibid.]

The possibility to control both the supply water temperature and flow in the
radiator system was reported in Paper I and Paper VII. The study showed that
the district heating return temperature can be lowered. A strength of the
proposed control method, which can be described as a combination of a low-
flow system and a system with normal flow depending on the heat load, is that
it automatically adapts to varying working conditions, such as long-term
changes in the primary supply temperature. Therefore, it always strives to
provide the lowest possible return temperature. Energy-saving measures,
signifying an increase in the oversizing of a system, represent examples of
changes that the control method can adapt to.

**Some innovations in the field**

Werner and Sköldberg have carried out an exposition of the knowledge and
research situation for district heating in the world [79]. Among other things,
this exposition highlights the question of whether conventional radiator
systems will be driven out of competition due to their not having been
developed in recent years. Such trends can be perceptible since air-borne
systems are chosen in so-called passive houses. In the present situation,
however, the installation of underfloor heating systems is common, and these
are especially favourable from a district heating point of view thanks to the
very low temperature level.

This section is intended to highlight a number of innovations in recent years
aimed at increasing the efficiency and competitiveness of district heating-
connected hydronic heating systems. The development is important both for
future competitiveness but also in view of the tremendous amount of radiator
systems that are in operation and will be so for a long time to come. The
construction of new buildings in Sweden amounts to only 0.6 percent per
year, relative to the existing building stock [ibid.].

In recent years, there has been a trend towards more “intelligent” district
heating substations, where the aim is to use modern technology to ensure a
proper operation and low return temperatures. Examples of projects exploring
this possibility can be found in [11], [12], [27] and [51]. The equipment
described in [12] was used in connection with the work presented in Paper
VII. In the report by Andersson and Werner [3], an evaluation of the so-called
function-integrated district heating substation, in operation, described in [51]
was reported and the return temperature reduction was estimated to 10-11°C.
Typical for this substation is, among other things, that the district heating flow is calculated and governed rather than regulated based on feedback control. By measuring temperatures and flows in the substation, the required flow is continuously computed. The result is a smoother control that can reduce the energy usage by avoiding overheating. The evaluation found that the benefits of a function-integrated substation exceed the cost of a conventional substation.

Another concept that aims at strengthening the competitiveness of district heating is the Swedish “Mathilda project” [41]. In contrast to the above concept, it seeks to achieve easier and less expensive manufacturing and installation of substations, including highly standardised modules for domestic hot water and space heating.

Demand side management involves the manipulation of the consumption of heat in order to optimise production and distribution of district heat, and has been widely investigated [39], [44] and [81]. In this process, the building’s potential to be used as heat storage is considered to be significant. The idea is to even out the heat power and flow needs of a district heating network, depending mainly on the fluctuations in domestic hot water loads. This way, the need for expensive and environmentally unsound peak production is reduced. This problem is also identified in connection with electric heating of buildings. So-called load shedding, when domestic hot water consumption is prioritised, is used for example in the substation described in [51]. Wernstedt and Johansson [80] achieved good results through a distributed load control system using load shedding in an entire neighbourhood where the substation that is currently best suited “lends” flow to the district heating network.

In the article [11], a dampened outdoor temperature with feedback from thermostatic radiator valves as the control method was questioned because of the difficulty in assessing a building’s thermal inertia and in responding to rapid fluctuations, e.g., due to solar radiation. Instead, a representative measurement of the indoor temperature is advocated. An indoor temperature measurement has also been used in the substation described in [51].

It should be pointed out that the control method developed in Paper I and Paper VII is not dependent on whether or not a traditional control method for the radiator system is employed. Rather, the aim is to use the optimal combination of supply temperature and flow for a given heat output.
A new concept for radiator systems, which has not yet been commercialised, involves decentralised pumps [16] and [17]. By equipping each radiator with a small pump, for which the control depends on the current heat demand, the need for valves and balancing is claimed to be eliminated and the total pump energy requirement could theoretically be reduced by 90 percent, or at least by 50 percent, with today’s components. Such demand control of the pumps allegedly reduces heat demand by 20 percent.

Olsson [43] has described a concept for district heating systems in which heat exchangers can be completely avoided thanks to a main network and several local systems separated by a pressure exchanger. End users are directly connected to the local systems by jet pumps. The aim is to create a robust system with low return temperatures. So far, however, the realisation of such a system has not, to the best of the author’s knowledge, been carried out.
Definition
The use of low temperatures in district heating systems presents numerous advantages. Therefore, a common performance measure for individual substations, or for whole networks, is a low district heating return temperature. In for instance Swedish literature, the term “good cooling of district heating water” is often used, which actually signifies the same thing. Both measures imply the utilisation of the energy content of each unit of water in the district heating network to an as high a degree as possible. The only actual difference is that cooling refers to the difference between the supply and return temperature.

What the optimum supply temperature in a district heating network should be is not easy to say in general terms. This has to be decided from case to case since it depends on several parameters; e.g., what return temperature the chosen supply temperature would result in, the composition of the district heating production and how its efficiency relates to the supply and return temperature, respectively, and the desired flow rate in the network. Moreover, there is a load-dependent variation of the supply temperature.

In several parts of this thesis, the expression optimal operation of the heating system is used. In the present context, this refers to the handling of the heating system and the substation in order to achieve the lowest possible primary return temperature for the given supply temperature.

Why important?
Many parts of the district heating system are favoured by low temperatures. Most types of heat production benefit from either a reduced supply or return temperature, or both.

Many boilers, especially boilers burning moist bio-fuels, today are equipped with flue gas condensation, which means that the return temperature
substantially affects the efficiency. Cogeneration production units usually benefit from a low supply temperature due to the power-to-heat ratio being increased. A low return temperature can also be beneficial; depending on, among other things, whether flue gas condensation is used. The coefficient of performance of heat pumps is increased if the supply temperature is decreased, and in some configurations also if the return temperature is decreased. The possibility of recovering waste heat from industries can improve if the network temperatures are lowered.

An increased temperature difference of the district heating water means that the flow rate in the network can be reduced, which in turn leads to less pump energy being required and to electricity being saved. Alternatively, the higher temperature difference increases the capacity of the network and enables more customers to be connected to the network, without having to increase the flow rate, or reducing problems with bottlenecks.

The heat losses in an existing network can be reduced if the temperatures can be lowered. Approximately one third of the heat losses can be attributed to the return pipe and two thirds to the supply pipe. In connection with the construction of new networks, a substantial decrease of the supply temperature can also lead the way to the use of plastic pipes, thereby reducing the installation cost, although the heat losses may not be reduced as a result of larger pipe dimensions being required when plastic pipes are employed.

An IEA study from 2005 [85] outlines several detailed analyses of the economic benefit of reduced temperatures. Among others, a comprehensive study of Rütschi [52] and a Swedish calculation model [61] for the evaluation of changes in system temperatures, depending on the composition of heat production, are referred to.

Werner has estimated that the value of a reduced return temperature amounts to 1 SEK/MWh,°C (approximately 0.10 EUR/MWh,°C) or 4-5 percent of the current district heating prices in Sweden, without including future benefits from a higher capacity of existing networks, see, e.g., [23] and [78]. An evaluation of the work towards increasing the temperature difference in the district heating network in Gothenburg, gave similar results. Furthermore, a pay-off time of less than three years was obtained [18].

The importance of low return temperatures is stated in the Euroheat & Power guidelines for substations [15]: “In general, the energy demand is decreasing. Specifically, the consumption for new buildings has decreased. This increases
the significance of having lower return temperatures, because a smaller consumption rate leads to smaller radiators.

The importance of individual analysis should also be pointed out. In some cases it may be rational to increase the supply temperature in order to reduce the return temperature and increase the heat output of flue gas condensers [24]. Therefore, it is not evident to say which is the optimal supply temperature in a district heating network. However, there is a general desire to maintain the return temperature as low as possible, i.e., to maximise the temperature difference of district heating water for the given supply temperature. This approach has been the basis for the control method presented in Paper I and Paper VII. Regardless of whether a district heating substation receives a relatively low or high supply temperature, the adaptive control algorithm adjusts the control parameters in order for the return temperature to be as low as possible.

Finally, one can conclude that, no matter what part of a district heating system one considers, higher temperatures than necessary inevitably lead to an increased use of primary energy resources.

**High return temperatures due to malfunctions in substations**

The main cause for high return temperatures can be attributed to malfunctions in the district heating substations. In the above-mentioned study of Werner [78], an annual mean return temperature of 47°C was found in Swedish district heating systems. Then, a decrease from 50°C was already carried out during the years 1993-2003. However, Petersson [48] estimates the possible return temperature to be 32°C with today’s state-of-the-art technology. Already in 1987, Winberg and Werner [83] found that the actual return temperatures during part load were higher than what was estimated. The study concluded that high return temperatures primarily depend on individual reasons since neither age, user category or size can fully explain the high return temperatures. Common malfunctions include components not being properly designed, components not working properly, deviations from standard designs, high temperature levels of heating systems, faulty connections and an incorrect control. Similar results were found by Råberger [53] and in the report [61]. Another important reason for the high return temperatures is hydraulic shortcuts in the district heating network [ibid.].
Zinko et al [85] reported that 60 percent of the discovered malfunctions can be ascribed to the heating system, 30 percent to the domestic hot water system and the remaining 10 percent to components in the substation such as the heat exchanger, pump and control equipment. One third of all malfunctions were related to comfort problems, while two thirds caused high return temperatures.

The studies presented in Paper I, Paper V and Paper VII were primarily devoted to a lowering of the return temperature. However, malfunctions were not considered. Instead, the possibilities of lowering the return temperature by improving state-of-the-art technologies were targeted.

**Low return temperatures in substations**

The most important issue for the return temperature is the heating system’s temperature level, which is described in the next section. Other factors that influence the return temperature include, as already mentioned, the choice between direct or indirect district heating connections of the heating systems and the substation connection scheme.

The influence on the return temperature from various connection schemes has been the subject of numerous studies. Simply put, one can say that connection schemes including cascading of heat exchangers have traditionally been attributed to having a positive impact on the return temperature, which is linked to the generally high radiator temperatures that have been prevailing. Thus, the two-stage substation is the most common connection scheme used in multi-dwelling buildings in Sweden. Examples of studies that have indicated a lower return temperature from the two-stage connection compared to the parallel connection scheme include those of Frederiksen et al [20], Snoek et al [59] and Gummérus [25], who also found that the Swedish three-stage connection (which is common in for instance Stockholm) gives a significantly lower return temperature.

The trend towards lower temperatures in radiator systems has reduced the benefits of cascading. Lindqvist and Walletun [37] have found that the connection scheme is of secondary importance in the selection of a new district heating substation. Of higher significance is the balancing of the secondary systems. Gummérus and Petersson [26] propagate for low-flow systems and the parallel connection, which is simpler and less expensive, and provide only a marginally higher return temperature. Euroheat & Power recommends [15] the use of a two-stage connection scheme in multi-dwelling
buildings where the return temperature from the space heating system is high. In other types of buildings, the employment of a parallel connection scheme is recommended. It is also concluded that “if a low-flow heating system providing low return temperatures is used, there will be little further benefit from the use of a two-stage connection scheme in terms of further cooling of the return water. In such cases, it is recommended that the more cost-efficient parallel connection should be selected.” [15]

An argument in favour of the two-stage connection scheme is that it provides an opportunity of avoiding that re-circulated domestic hot water will mix with incoming town water and increase the return temperature, instead mixing with hot water that has already been pre-heated [59]. This is, however, not the result of the cascading in itself but in fact the result of the two-stage connection heat exchanger design, which allows for this type of connection of re-circulated hot water. This is further discussed in Paper V.

The influence of performance of the hydronic heating system on primary return temperature

The guideline also states that [15]: “The amount of heat utilised from the circulating district heating system water depends mainly on the design and adjustment of the building’s internal heating systems”. In a study of district heating substations in operation, Råberger [53] found that high return temperatures are mainly due to the return temperature of the radiator system. However, extremely high return temperatures depend on malfunctions in the substation.

Furthermore, it has been concluded in [15] that: “regardless of the choice of design temperatures for the radiator circuit, balancing of the system has a decisive effect on operating performance”. This was also shown by Trüschel [72] where the value of balancing of three heating systems was estimated to give a pay-off time between 1½ and 5½ years.

A low-flow system could result in a reduced primary return temperature, as already mentioned in the section on Space heating – System temperatures. The benefits with regard to the primary return temperature from adjusting the flow according to the heat load are known. The idea of using an optimal combination of flow and supply temperature was conceived by Frederiksen and Wollerstrand [19], and this theory was further studied by Volla et al [74] and Snoek et al [59]. The guidelines from Euroheat & Power [15] state that the lowest return temperature is obtained by varying the flow according to the consumption. If such a variable flow is used, it is controlled by thermostatic
radiator valves either in combination with a constant supply temperature or with an outdoor temperature-compensated supply temperature. Langendries [33] suggested a central control of the flow rate through the pump’s rotating speed, but then claimed that it appears to be a rather difficult and expensive system. Petitjean [50] proposed a lowering of the pump speed at low heat loads, when the thermostatic radiator valves are almost fully open, but found it problematic to determine which parameter to use for the control of the pump speed.

Paper I and Paper VII present the development of a control algorithm that finds the optimal combination of flow and supply temperature of the radiator system. Although the control algorithm is not fully developed and evaluated, it shows that it is possible to reduce the primary return temperature.
Secure energy supplies are taken for granted by most of us. At the same time, we have become increasingly dependent on energy and a disruption of energy supply has a significant impact on our society. A major disruption in the supply of heat under cold weather conditions also poses a threat to our health, especially for the elderly and otherwise weak individuals.

**District heating - generally reliable**

It can be argued that the advance of the most centralised form of building heating represented by district heating, sometimes serving a majority of buildings within a town, could render building heating more vulnerable in certain respects. On the other hand, as presented in this thesis, district heating possesses a great potential for upholding heat supply.

District heating is generally considered to be a reliable technology, as demonstrated in a Finnish study among others [38]. Skagestad and Mildenstein [58] claim that “the reliability provided by a properly designed, constructed, operated and maintained district heating system is greater than most buildings can achieve on their own”. In the U.S., cogeneration is often considered to be a very reliable form of energy supply [73] and [29]. Six and a half percent of commercial buildings in the U.S. are heated with district heating, and there are 2500 networks typically located in densely populated areas such as business districts, universities, hospitals, military establishments and airports. The reliability of district heating and cooling systems provided by cogeneration is often emphasised. Those advocating a district heat expansion in the U.S. often point out that “Operational reliability has been a hallmark of the district heating industry” [29]. Funk [22] suggests the use of small-scale cogeneration in conjunction with emergency generators to provide an enhanced reliability.

District heating is also generally stressed to contribute to secure heat supplies because of the flexibility regarding heat production which can alleviate the dependence on imported fuels [10] and [60].
A report by the Swedish Energy Agency [66] claims that district heating in Sweden generally maintains a high level of reliability as a result of few supply disruptions and high fuel flexibility. However, it also provides warnings regarding the consequences of a prolonged power failure in the form of severe strains on the society and the risk of freeze damage in buildings, which is mainly attributed to the electricity dependency of the district heating end-user.

When discussing the economic optimisation of a reliable energy supply, i.e., how much it costs to increase the security of supply in relation to the estimated savings of fewer supply disruptions, the interruption or interference for individual customers is considered. This was not the intention of the present work, but rather to study large, extensive disruptions that could pose a threat to a city or a community and cause serious consequences, something that is difficult to estimate in monetary terms.

Power failures

Having mentioned that district heating is generally a reliable technology, we now focus on the dependency on electric power in district heating systems. We will not get into the occurrence of outages and reasons as such, but simply note that most types of heating systems are more or less dependent on electricity. In the case of a power failure, electric heating obviously cannot function, nor can heat pumps. Most systems with boilers are also dependent on electricity since burners, control equipment and pumps are electrically driven.

The present work is devoted to what happens in buildings connected to district heating. If any heat is to be transferred, the district heating network needs to function, at least to a certain extent. A Swedish study has demonstrated that conditions differ between networks [64]. Some district heating utilities have back-up power to keep the system in operation, while others do not, some are only able to protect their network from freezing. The issue is however important, not only because of the possibility of natural circulation arising in the internal systems of buildings, but also for assuring whether customers with back-up power, such as hospitals, can expect to receive district heat.

If district heat supply can be maintained during a power failure, this will represent a good sales argument for district heating in comparison with heating systems that are inherently dependent on power supply – heat pumps have already been mentioned as an example in point.
Provided that production and distribution of district heat can be maintained, a direct connection in its simplest form (with no admixing of hydronic return water) implies an inherent ability to supply district heat during a power failure.

A special type of direct connection has been employed in district heating systems in Central and Eastern Europe, where jet pumps (ejector pumps) are often used in substations, rendering it possible to deliver heat, even if the customers have no electricity [40] and [42]. These jet pumps are generally uncontrolled but have provided very robust substations. The virtue of the independence of electricity was already pointed out in two papers from 1974 by Schmidt [57] and Deckert [9]. Controlled jet pumps are used to a certain extent in district heating systems, for example in Germany, and have been studied by Brumm [4] and Olsson [43] among others. However, these more sophisticated jet pumps, which reduce the significantly higher district heating supply temperature and differential pressure to match the level of the secondary heating system, often have self-closing valves to prevent damage from district heating water entering the secondary system in the event of a power failure.

The literature review presented in Paper VI and in the Swedish project report [34] (of which the latter is somewhat more comprehensive), demonstrates that, in Swedish risk planning, the potential for heat supply in district heating systems in the event of a power failure has been largely overlooked. This is attributable to the common use of indirect district heating connections which are considered to involve a dependency on electricity.

Besides supplying heat to customers with back-up power, the matter of district heating during a power failure is important for other reasons. First of all, an interruption in the heat supply represents a considerable potential threat to numerous people, especially elderly people and individuals in need of care. Shortcomings in the preparedness for elder care in case of a power failure has been demonstrated [70] and it was found that more than 40 percent of the facilities in Sweden lacked access to back-up power or heat. Another study [8] presented similar results.

One of the most well known power failures occurred when an ice storm hit Canada in 1998, leaving 4.7 million people without power and heat for a prolonged period in the middle of winter. This demonstrated the need for planning and the benefit of emergency preparedness [31] [35]. There were no district heating systems in the area; instead heating was primarily obtained
from electricity and oil. The blackout caused extensive evacuations; many
people could move in with relatives and friends while others had to stay in
public shelters. Studies have shown that people felt that the most significant
strain consisted in trying to keep warm [69].

The storm ‘Gudrun’, that struck southern Sweden in January 2005, caused
widespread, long-lasting blackouts and became a reminder of how vulnerable
our society is when energy supplies fail. Luckily, the weather was relatively
mild and larger towns with district heating systems did not have as long-lasting
power failures as smaller towns without district heating [65]. As described in
Paper VI, the district heating utility in one small town experienced that heat
supply could in fact be maintained to a significant degree, and that this could
be attributed to the occurrence of natural circulation in the connected
buildings.

The magnitude of the possible district heat supply during a power failure
might be crucial for some cogeneration production units that depend on the
district heating network for cooling of the power generating process. In many
towns, preparations are made for the possibility of starting up local power
plants and establishing a local power grid, so-called island operation. This
enables vital social functions to be supplied with electricity.

In August 2003, 50 million people in the north-eastern USA were affected by
a power failure, and certain areas were without power for four days. Carlson
[7] describes how various small cogeneration systems acted in connection with
the power failure. The vast majority, including units not designed for stand-
alone operation, functioned satisfactorily during the blackout. The heat load
was rather low during the time in question, but the ability to maintain, or
restore, the power supply in these systems was of considerable importance for
minimising the impact of the blackout. This experience demonstrates the
tremendous advantage of cogeneration.

In a review of the situation of district heating research in the world, Werner
and Sköldberg [79] raised the long-term research issue “How can the
dependency of district heating on electricity be reduced?”. As already
mentioned, the reliability of district heating is high from a production
standpoint, thanks to the high fuel flexibility. However, there is a strong
dependency on electricity for pumps, both in the network as well as in
buildings. Further, the following questions are posed: “Is it possible to create a
district heating system that, in practice, can maintain heat supply in the event
of a long power failure? What are the implications for district heating
customers during a long power failure?" [ibid.] The studies described in Paper II, Paper III, Paper IV and Paper VI have shed light on these issues.

**Natural circulation can ease electricity dependency**

Hydronic space heating systems built during the early days of central heating were constructed for natural circulation. When water is heated, its volume increases, and the water rises in the system. In reverse, when the water is cooled off in the radiators, the density increases and the water descends back to the heat source.

More information regarding natural circulation can be found, for instance, in reference [28]. By using large pipe dimensions in the distribution system and a boiler with a low flow resistance, pressure losses can be kept to a minimum and it becomes possible to achieve a sufficient circulation flow without any assistance from a pump [45].

The studies performed within the framework of the present thesis have comprised extensive field studies, and have in fact revealed that significant natural circulation can occur in many types of buildings. Even a limited heat supply extends the time it takes for a building to be cooled down to an unacceptable level. If the indoor temperature drops, the heat rate from the radiators is raised [76] and the return temperature decreases, which in turn enhances the natural circulation, and therefore further slows down the cooling of the building.

Modern heating systems are not designed for natural circulation and, consequently, the conditions for a sufficient amount of natural circulation to take place vary greatly. In order to take into account such a variation, guidelines and recommendations have been addressed to all concerned parties, i.e., authorities, district heating utilities, manufacturers, property owners, caretakers and residents, to inform them of how they can be appropriately prepared. Among other things, the recommendations, which are more thoroughly described in the Swedish report of the project [34], entail the following:

- If one quickly wants to get an idea of how the heating system in a certain building works in the event of a power failure, one can perform a simple experiment.
Based on the performed field tests, a matrix has been developed for the purpose of assessing the possibilities for natural circulation in a building based on building characteristics, such as age, design, type of radiator system, etc. The idea is to estimate how much of the capacity for natural circulation that is lost due to various obstacles in the system. Typical obstacles for natural circulation in modern heating systems are described in Paper II.

In order for district heating to be delivered during a power failure, it is crucial that the operation of the district heating network can be maintained. Back-up power is therefore required in order for the heat production and the distribution, i.e., the circulation pumps in the network, to be maintained. An increase of the supply temperature in the district heating network during a power failure can cause a higher supply temperature in the radiator system and thereby enhance the natural circulation. The extent to which this can be achieved must be assessed from case to case.

By mapping out buildings in different housing areas, one can obtain a good estimate of the sensitivity to power failures of buildings in different areas and of different categories of buildings. One can assess which categories are well prepared and which are in need of specific actions, such as evacuation of tenants or installation of back-up devices. This is relevant for both authorities and building owners.

Staff responsible for the operation of the buildings has a vital role if a power failure should occur. The control valve actuator can be of the self-closing type and the valve must then be opened manually. The opening of a control valve requires some caution. Valves are sometimes generously dimensioned and if fully opened, the primary circuit flow rate becomes very large. Since the amount of heat that can be transferred with natural circulation is limited, this leads to an unnecessarily large flow that “steals” differential pressure. The situation is different with regard to the domestic hot water system. The primary circuit control valves pertaining to this are often of the self-closing type and should not be opened manually, due to the risk of scalding from too hot tap water.

Examples of how the design of some components can prevent or limit natural circulation have been found. The most obvious was mentioned above; control valves that close in case of a power failure. There are no
records of such control valves being used in heating circuits. However, electromagnetic actuators are sometimes employed and their design is such that they inevitably close if they lose power. These actuators should be avoided if one wants to facilitate natural circulation. Another major limitation for natural circulation that has been found is a type of substation where the heat exchanger is installed “upside-down”, i.e., a heat exchanger where the outgoing secondary flow leaves the heat exchanger at the bottom. This causes the natural circulation flow to run backwards and the heat exchanger to function as a co-current heat exchanger, which greatly reduces the heat transfer.

**A turbine-driven pump device can further reduce the electricity dependency**

Since a sufficient natural circulation flow does not appear in all types of buildings, an idea originally presented by Johnsson [30] has been developed, namely to let a turbine, located on the primary side in a substation, drive the heating system circulation pump. The district heating flow to the heat exchanger is normally throttled by a control valve in series with the heat exchanger, in which case one could say, that a large part of the differential pressure in the district heating network is not utilised, as it will be under the proposed concept.

In order to verify whether the idea worked in practice, a prototype was developed in collaboration with a pump manufacturer. A pump was used as a turbine, which represents a common solution for small applications, cf. e.g., Williams [82]. This has the advantage of the cost being minimised since pumps are readily available in numerous configurations at relatively low prices.

Paper IV describes a field experiment with the prototype, and it was concluded that the device could function as a back-up system for heat supply even if the technology required some refinement. Thus, the tests showed that a careful dimensioning of the components was necessary.

The prototype had been designed for application in a mid-sized building. It is not yet clear to which extent the concept can be useful in very small houses, due to the fact that both turbine and pump efficiencies drop off under such conditions.
METHOD

Although much of the work in the investigations presented herein consists of field studies, computer simulations have provided an important supplement. Especially Paper III and Paper V present the results of exclusively simulations. The advantage of simulations is that they are generally cheaper and faster than studies in the field or in the laboratory. Moreover, one can easily study the effect of varying individual parameters. However, simulations are associated with methodological considerations and verification of results in the field is essential.

There exist numerous investigations on modelling of district heating systems. Gummérus [25], for instance, described deterministic modelling of all components in a district heating substation and a radiator system by the so-called lumping technique. This corresponds to all heat-transferring components being divided into sections, where each section is considered as a stirred tank.

For the simulations carried out in connection with the work presented in Paper III, Paper V and Paper VI, the commercial software Simulink was used. The models are based on the technique described in [25], but they have been developed over the years at the department, as described by Wollerstrand [84] and Persson [47].

In connection with the studies presented in Paper III and Paper VI, the models were developed in order to study natural circulation. These modifications are described in Paper III together with a simple, static calculation of the flow distribution in the radiator system during natural circulation.

Paper I and Paper VII reported on yearly mean primary return temperatures for different heating system temperatures with respect to the outdoor temperature duration. The mean temperatures are flow-weighted, which is equivalent to collecting all the return water flow in a well-insulated container and measuring the mean temperature. This approach has been described by Gummérus [25].
The calculation of optimal combinations of flow and supply temperature in the above-mentioned papers has been achieved through an iterative process where the heat load, the primary supply temperature and the minimum allowed radiator flow were given and the lowest possible primary return temperature was set as the target.
CONCLUDING DISCUSSION

Clearly, the ideas presented in this thesis are mostly as such in many ways not new. For example, the idea of determining the optimal combination of supply temperature and flow in a radiator system in order to obtain the lowest possible return temperature was presented more than twenty years ago. Central heating systems were designed for natural circulation before circulation pumps became common practice. The ideas regarding the turbine-pump device and various connection schemes for substations have also been discussed previously.

The main ambition of this thesis has been to bring these ideas closer to practical applications. For this purpose, I hope to have contributed, through the work presented herein, to the implementation and verification of these ideas in the field. Modern building automation has made it possible to accomplish control of radiator systems including a control of the flow rate as well as more sophisticated connection schemes for substations. Although the laws of physics governing natural circulation date back a long way, no studies of natural circulation in pump-operated heating systems seem to have been presented previously. Last but not least, a prototype of the turbine-pump device has been developed and tested.

Reflections on the studies aiming at lowering the return temperature

A new control algorithm has shown promise for a lowered district heating return temperature through a variation of not only the supply temperature but also the flow rate in the radiator system. This was done by controlling the pump speed. The forthcoming heating season (2009-2010) will be used to evaluate and refine the control method.

There is further potential for lowered return temperatures by adapting connection schemes for substations in the light of increasingly lower temperatures in hydronic heating systems. The results presented in this thesis can be regarded as preliminary. An interesting next step would be to build prototypes and test them in practice.
Reflections on the study of electricity dependence of district heating

The study on district heating and power failures has shown that modern heating systems present good opportunities for maintaining an acceptable heat supply by natural circulation. The project is essentially completed and the results have been distributed to interested parties, and have been met by great interest. The investigation can possibly be extended to a certain extent; there was, for instance, no time to study natural circulation in underfloor heating systems. The most important aspect is, however that the results be used, as more and more authorities and energy companies become interested in risk and vulnerability issues. The work was carried out in cooperation with the municipality and the district heating utility in Malmö, and the obtained data will be employed as a basis for their forthcoming work. The district heating company is working on providing for back-up power in all of their district heating systems in Sweden.

Finally, in light of an increased interest for a safe energy supply in general and possibilities for island operation in particular, one could argue that all district heating networks should have at least a small cogeneration plant. This means that one can significantly enhance the opportunity to provide critical activities in a town with both electricity and heat. As also demonstrated by this work, there is a great potential for district heating customers that are without electricity to actually receive district heat.

The turbine pump leaves an interesting opening for further studies. According to the findings, it showed potential to work as a back-up device. The idea of utilising it for continuous operation has not been studied, but a quick look at the prerequisites for such usage shows much promise, as presented below. This is especially the case if one considers a synergy effect with the developed control method using a load-dependent flow rate in the heating system.

Suggestion for future studies on continuous operation of turbine-driven circulation pump

In order for the hydraulically least favourably situated substation in a district heating network to obtain the required differential pressure, the vast majority of all other substations are exposed to a differential pressure that is higher than what is required. Our investigations have prompted some in exploring the suggested possibility of using the device for continuous operation, as was presented in Paper IV. The idea is thus, to substitute the electricity driving the
circulation pump with the kinetic energy of the district heating flow which is otherwise not utilised. Although most of the electric energy supplied to pumps, in the network as well as in the heating system, is converted to kinetic energy and subsequently turned into heat energy which causes a slight increase of the water temperature, it represents a loss of exergy in the sense of the second law of thermodynamics. This is due to useful work being converted to heat. The concept means that less electricity, as a whole, needs to be added to the system, since the turbine pump implies a recovery of work. Consequently, the otherwise inevitable exergy loss can be reduced.

Continuous operation of the turbine pump requires further studies. However, the working conditions of the turbine pump become less favourable for a decreasing heat load, due to the increasing flow ratio between the secondary and primary sides, as demonstrated in Paper IV. Consequently, it would be interesting to study the turbine pump in combination with a variable flow in the radiator system.

Figure 2 was taken from Paper IV, but now includes the flow ratio for the optimised radiator temperature programme presented in Paper I and Paper VII. Since the optimisation signifies that the flow is reduced according to the heat load, it better follows the primary flow reduction and hence, the flow ratio becomes more even. Particularly, it does not reach extremely high values for low heat loads as is the case with the other temperature programmes using a constant secondary flow rate. The extent of the increase of the ratio at low heat loads is a matter of the choice of lower limit for the secondary flow.
Let us now use the relation for the required aggregate efficiency of the turbine pump, as defined in Paper IV ($\eta = (\Delta T_p / \Delta T) \cdot (\Delta P_p / \Delta P)$), and evaluate the optimised temperature programme. The following assumptions are made:

With the 55/45°C temperature programme, the required secondary differential pressure is set to 0.5 bars. A 60/40°C programme corresponds to the flow being halved (twice the temperature drop) and the differential pressure then becoming a quarter of 0.5 bars. Accordingly, for the 80/30°C programme the pressure differential is only one twenty-fifth of 0.5 bars. For the optimised programme, the secondary flow and differential pressure is individually computed for each outdoor temperature, as a result of the secondary flow varying.

The pressure and temperature difference on the secondary side are now known, and the primary temperature difference is also given (Paper IV). Regarding the primary differential pressure, two cases are assumed: one where
the substation is situated very close to one of the circulation pumps of the district heating network, and the other where the substation is situated far from the pump. For the two cases, the differential pressure at maximum load is set to 6 and 1.5 bar and the minimum to 1.5 and 1 bar. The differential pressure is assumed to be constant for an increasing outdoor temperature up to the supply temperature breakpoint, after which it is supposed to linearly decline to the minimum value. A pressure drop of 0.5 bars is also subtracted from all values in order to account for the pressure drop in substation components. All in all, we end up with eight efficiency curves, two for each temperature programme, of which seven are displayed in Figure 3.

![Figure 3](image-url)

*Figure 3* The required aggregate efficiency for the turbine-pump for various radiator system temperature programmes as a function of the outdoor temperature.

The 55/45°C programme in a substation with a low differential pressure would demand an efficiency higher than 100 percent. For the high-pressure substation, one can just barely catch a glimpse of the curve in the upper left corner. The required efficiency for the 60/40°C programme could possibly be sufficient for most of the operating range but it clearly becomes difficult to
handle low heat loads. The low-flow system has far better possibilities, even if problems still occur at high outdoor temperatures. However, with the optimised programme, the aggregated required efficiency never exceeds 3 percent under the assumptions made. Although this is a simple calculation, it shows that there is definite potential for a turbine-driven circulation pump for continuous operation, when employing a pump as the turbine. The fact that the required efficiency is low also indicates that an indirect (electric) connection between the turbine and the pump, providing more sophisticated control, could be used instead of the simple direct (shaft) connection that was employed for the prototype - especially considering that an indirect connection involves additional losses in the generator and motor.

Let us now, finally, have another look at the figure presented in the introduction. Only, in this case, it is completed with the suggested future study, cf. Figure 4, which can be a way of combining the work regarding the lowering of the return temperature and that involving reducing the electricity dependency.

![Diagram](image)

**Figure 4** The objective of the thesis, as shown in Figure 1, supplemented by the suggested future study.
Thus, the combination of a lowered return temperature and a reduced electricity dependency could be achieved by a development of the turbine pump. In light of an increasing focus on primary energy usage, savings of electricity is highly valued; even if the initial saving seems to be small. For example, the recast of the EU directive 2002/91/EC on energy performance of buildings [6] states that “a primary energy indicator and CO\textsubscript{2} emissions indicator shall be used”.
<table>
<thead>
<tr>
<th>#</th>
<th>Author(s)</th>
<th>Title</th>
<th>Source</th>
</tr>
</thead>
</table>


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(The storm Gudrun and space heating. Experiences from power failure with focus on building heating), Report ER 2005:33, 2005.


OPTIMISED SPACE HEATING SYSTEM OPERATION WITH THE AIM OF LOWERING THE PRIMARY RETURN TEMPERATURE

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ABSTRACT
The paper presents results from a study aiming at minimising the primary return temperature from a district heating (DH) substation by optimising the control algorithm for a space heating system connected to the DH network via a heat exchanger (HEX).

As shown in a previous study, an optimal (i.e., minimum) DH return temperature exists for every heat load. By varying both the radiator flow and the radiator supply temperature, this optimum can be found.

A space heating system is traditionally designed for a constant circulation flow rate combined with a suitable control curve for the space heating supply temperature as a function of the outdoor temperature. Optimal choice of the control curve varies from case to case and is an issue both we and others have dealt with in previous work. In the paper, theoretical control curves for optimal control of the space heating system in order to minimise the DH return temperature has been derived by calculating how supply temperature and circulation flow should be varied with the heat load. The estimated gain was found to vary strongly, depending on the actual conditions. However, assuming realistic conditions, it was seen that the gain can be as much as a reduction of 6°C of the DH return temperature from the radiator HEX on yearly average.

This paper presents theoretical knowledge and shows results supported with practical experiments. Based on these results, a method for adaptive choice of parameter values for an optimised controller can be developed. One of the advantages with such an algorithm is that it will automatically adapt to changed conditions, e.g., a variation in primary supply temperature.

Keywords: District heating, Space heating, Control System, Low Return Temperature

INTRODUCTION
The following work deals with the operation of hydronic space heating systems, indirectly connected to a district heating (DH) network, how to choose temperature programme and circulation flow, and how this affects the DH return temperature. A new method using a variable, load dependent flow rate will be described and analysed.

Lowered return temperatures, or increased cooling, of DH water is always a relevant topic in DH technology. The efficiency of both heat production and heat distribution will be higher if the energy in the circulated DH water is used to an extent as large as possible. Many studies have shown that the return temperature mainly is determined by the parameters in the house-internal systems, for example supply and return temperatures and circulation flow in the space heating system.

Traditionally, hydronic heating systems work with a (more or less) constant flow rate. However, in previous work [3], [4] and [6] it is shown that by varying the flow rate, depending on the heat load, it is possible to lower the DH return temperature.

OPERATION OF THE RADIATOR SYSTEM IN GENERAL
Space heating systems dealt with in this work is conventional 2-pipe radiator systems, connected to a DH substation, see Figure 1. Note that we exclusively deal with so-called indirect connections, i.e., that a heat exchanger (HEX) hydraulically separates the DH and radiator systems, which is the predominant method used in Sweden.

Figure 1 Schematic picture of a 2-pipe radiator system in a building connected to DH.

Traditionally, the heat output is controlled by varying the supply temperature to the radiators according to a control curve based on the outdoor temperature, the building’s heat losses and the radiators’ thermal characteristics. The circulation flow is not controlled in the substation and although it might be throttled by thermostatic valves in the radiators, the flow can be considered to be constant. Frederiksen and Wollerstrand already in 1987 [3]...
showed that in every radiator system, for every heat load and DH supply temperature, there is a flow rate and a supply temperature that gives the lowest DH return temperature.

Regarding the temperatures in the radiator system, there have been different recommendations. Today, generally lower secondary temperatures are used (60/45, 60/40 and 55/45°C), while traditionally higher temperatures (e.g., 80/60°C) has been prevailing.

Radiator systems are almost always oversized, often up to 100 percent or more; see for example references [5], [7] and [8]. What is the consequence of a radiator system being oversized? If no actions are taken, the indoor temperature will be too high. A system with well-functioning thermostatic radiator valves can, at least in theory, throttle flows and achieve the desired indoor temperature. Other possibilities are that the tenants by themselves will close the radiator valves, complain to the caretaker – who can change the control curve – or simply open a window.

Figure 2 shows three different graphs. Each one shows a traditional 80/60°C system (red curves) together with a modified temperature programme (orange curves) to compensate for an oversizing of 100 percent of the whole system (HEX, radiators and flow rate). The vertical line in each graph indicates the design outdoor temperature, \( T_{\text{DOT}} \), which in this case is set to \(-15\)°C. An oversized system can be considered as a correctly designed system that operates at a wider outdoor temperature range than the actual by moving \( T_{\text{DOT}} \) to the left. According to this reasoning, the secondary temperature programme can be converted to the new temperature range (which is doubled in the case with 100 percent oversizing). Assuming that heating is needed for outdoor temperatures up to 17°C, the original temperature range is 17 \(- (-15) = 32\)°C and the 100 percent oversized range becomes \( 2 \times 32 = 64 \)°C and the new \( T_{\text{DOT}} = 17 - 64 = -47\)°C. In other words, the system is able to achieve the desired indoor temperature even at \(-47\)°C.

With 80/60°C at \(-47\)°C, one will have 55/45°C at the real \( T_{\text{DOT}} = -15\)°C. This temperature programme is shown in the first graph and corresponds to the case when the supply temperature is lowered, without any other action taken. In the second graph, the idea is to keep the temperature drop of 20°C at \( T_{\text{DOT}} \). The flow has therefore been adjusted (the original pump being oversized) and we get a 60/40°C system instead. This alternative gives a lower return temperature and reduced risk of noise in the system. Finally, the third graph shows what is usually termed a low-flow system. This method was presented in the 70s; see for example [1]. Theoretically, this would be the case if perfectly functioning thermostatic radiator valves were used. In practice, the system has to be balanced hydraulically to avoid imbalance and overheating of parts of the building.

The advantages with such a low circulation flow rate are that the pressure drop will be relatively small, and that all radiators will have approximately the same pressure differential, which simplifies design and balancing of the radiators [2]. Further, there is a reduced risk of noise and less pumping energy is required. Thermostatic valves will have larger authority and there will no longer be any need for balancing valves on individual risers.

The high secondary supply temperature used in combination with a low circulation flow makes the system more sensitive to changes in the primary supply temperature. If the primary supply temperature is decreased, the control valve opens and increases the primary flow through the HEX. In such a case, the primary return temperature will increase.

**OPTIMISATION OF THE RADIATOR PROGRAMME – THEORY**

How is the primary return temperature, \( T_{\text{pr}} \), affected by a changed radiator flow rate and supply temperature? The heat flow from the primary water, via the secondary water, to the indoor air can be described by:

\[
\dot{Q} = \dot{m}_s \cdot c_p \cdot (T_{ps} - T_{pr}) = \dot{m}_s \cdot c_p \cdot (T_{ss} - T_{sr}) = K_{rad} \cdot LMTD^m_{rad}
\]

(1)

The logarithmic temperature difference, \( LMTD^m_{rad} \), between the radiator surface and the indoor air is defined as:

\[
LMTD^m_{rad} = \frac{(T_{ss} - T_{sr})}{\ln \left( \frac{T_{ss} - T_r}{T_{sr} - T_r} \right)}
\]

(2)
The heat transfer capacity from the radiator surface is practically constant, i.e., it is not affected by the magnitude of the circulation flow through the radiator. This is due to the fact that the heat transfer resistance between the water in the radiator and the inside of the radiator wall is at least ten times lower than the resistance between the radiator surface and the surrounding air. However, a reduced flow means that every unit of water will be in the radiator for a longer time, and hence the cooling of the water will be larger. The largest possible theoretical temperature difference is limited by the primary supply \( T_{ps} \) and the indoor air \( T \) temperature.

In contrast to the radiator, the performance of the radiator system HEX is dependent on variations in the flow. This is a water-to-water HEX where the primary and secondary heat transfer coefficients are of similar magnitude. A lower flow has a negative influence on the heat transfer which results in a reduced cooling of the primary water. How could a lower radiator flow still be of interest?

The transferred heat in the radiator HEX is given by the following equation:

\[
Q = k \cdot A \cdot \text{LMTD}
\]  

(3)

The overall heat transfer coefficient is defined as the sum of all the resistances from the primary to the secondary side of the HEX. The most significant resistances are the convective (between water and HEX wall material). The conductive resistance in the wall material can generally be neglected.

Because of the relatively moderate temperature variations in a DH substation the convective heat transfer coefficient can be assumed to be a function of the flow only, according to: (cf. [9])

\[
\alpha = c_0 \cdot m^n
\]  

(4)

Using (4) the overall heat transfer coefficient, \( k \), can be written as:

\[
k = \left( \frac{1}{\alpha_p} + \frac{1}{\alpha_s} \right)^{-1} = c_0 \cdot \left( \frac{1}{m_p^n} + \frac{1}{m_s^n} \right)^{-1}
\]  

(5)

The last substitution assumes symmetrical flow channels on primary and secondary sides of the HEX. The equation tells us that a lower flow means lowered heat transfer capacity. However, it is possible to show that, if one flow is significantly larger, the impact of a changed magnitude of the lower flow is reduced.

Consider a typical symmetrical plate HEX in a DH substation. In a high flow system, e.g., an 80/60°C system which is oversized by 100 percent and is operated as a 55/45°C system, the temperature drop at DOT is 10°C, while the primary side temperature drop can be 50°C or more. The relation between the primary and the secondary flow is then inversely proportional to the relation between the respective temperature drops. Now, compare the influence on the overall heat transfer coefficient using a temperature drop of 10°C and 20°C (half the flow), respectively:

- 10°C: \( k = 1 / \left( \frac{0.5^{0.7}}{10^{0.7}} \right) = 0.049 \)
- 20°C: \( k = 1 / \left( \frac{0.5^{0.7} + 20^{0.7}}{1} \right) = 0.042 \)

Consequently, halving the flow only gives a moderate decrease (14%) of the heat transfer capacity. It is not until we get approximately the same flow on each side that the decrease in heat transfer capacity becomes considerable. On the other hand, a decreased flow results in temperature changes in the radiator system.

We must therefore study the parameters’ total influence on the heat transfer, which most easily is done numerically.

In the first graph in Figure 3, it can be seen that the overall heat transfer coefficient, \( k \), in the HEX continuously decreases with an increased temperature drop in the radiator system. This is caused by a decreasing heat transfer coefficient on the secondary side of the HEX due to the smaller flow. At the same time, the LMTD increases. Note that the primary flow is varied in order to keep the level of transferred heat constant which means that the product \( k \cdot \text{LMTD} \) is constant.

When the secondary flow rate decreases, the primary return temperature begins to decrease until it reaches a minimum level. After the optimum, it starts to increase again. The minimum primary return temperature is achieved at a secondary temperature drop of 40-45°C in this case.

This HEX has been designed for a secondary flow that is significantly larger than the required primary flow. Because of this, and the fact that the HEX is symmetrical, the heat transfer on the primary side is relatively small. If we know that the radiator system will operate with a high temperature drop, the HEX can be designed differently. The next graph shows the situation when the HEX has been made narrower but longer, with the same heat transfer area, to better suit the new flow rates. This can for example be made by a so-called two-pass HEX, i.e., a long HEX “folded” in the middle.
The overall heat transfer coefficient is now significantly increased and the primary return temperature has been decreased by several degrees. Its minimum is now 5°C less and has moved to a secondary temperature drop of 50-55°C (see the lower graph in figure 3).

**Optimised temperature programme**

The design conditions for the HEX are normally given at full load, \( T_{DOT} \). However, space heating systems are almost always working at part load, which makes the HEX oversized from a design point of view. This means that the highest possible cooling of primary water is achieved by increasing the radiator supply temperature while the circulation flow rate is reduced; see the dashed lines in Figure 4 showing the optimal temperatures when the radiator flow is varied. As a reference, the grey line shows the primary return temperature for a high flow system (55/45°C).

To be able to quantify the comparison between the different ways to operate the space heating system, one must take the duration of the outdoor temperature into account. The resulting weighted, primary return temperature for a high flow system (55/45°C) is shown for comparison (grey curve).

Figure 4 A 100 percent oversized radiator system compensated by an optimised temperature programme (variable flow). The primary return temperature for a high flow system (55/45°C) is shown for comparison (grey curve).
Table 1 Difference in yearly weighted primary return temperature from the space heating HEX relative the reference case (bold) [°C]. For each temperature case the magnitude of the circulation flow relative the reference case (= 1) is given. Oversizing means that both the radiators and the space heating HEX are oversized.

<table>
<thead>
<tr>
<th>Oversizing [%]</th>
<th>Type of radiator programme</th>
<th>Relative flow</th>
<th>Return temperature reduction with HEX:</th>
<th>Prolonged</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>standard, 80/60°C</td>
<td>1</td>
<td>44.9</td>
<td>-0.8</td>
</tr>
<tr>
<td>0</td>
<td>optimised (0.2-1)</td>
<td>(0.2-1)</td>
<td>-1.8</td>
<td>-5.8</td>
</tr>
<tr>
<td>100</td>
<td>55/45°C (high flow)</td>
<td>2</td>
<td>-10.2</td>
<td>-10.3</td>
</tr>
<tr>
<td>100</td>
<td>60/40°C (normal flow)</td>
<td>1</td>
<td>-12.2</td>
<td>-12.3</td>
</tr>
<tr>
<td>100</td>
<td>80/32°C (low flow)</td>
<td>0.4</td>
<td>-13.4</td>
<td>-14.6</td>
</tr>
<tr>
<td>100</td>
<td>optimised (0.2-0.5)</td>
<td>(0.2-0.5)</td>
<td>-16.1</td>
<td>-18.1</td>
</tr>
</tbody>
</table>

Four main conclusions can be drawn from the table:

- An oversizing in itself can give a large gain in primary cooling provided that some kind of compensation is made for the system to work properly, i.e., achieve the desired indoor temperature.
- By optimising the system (varying flow rate) the primary return temperature can be further decreased.
- An extension of the HEX is further reducing the primary return temperature in systems using a low secondary flow rate.
- Regardless of the degree of oversizing, the combination of an optimised programme and a prolonged HEX gives a substantial reduction in the primary return temperature.

The lowest acceptable level of the circulation flow rate during the optimisation of the radiator circuit was set to 20 percent of the original flow. There is no specific reason for this choice and it might in practice be suitable to use another level. To investigate how sensitive the results are with respect to the chosen level, the calculations were performed using 40 percent instead (which corresponds to the flow used in the low flow system). With no oversizing, the result was −1.6°C (compared to −1.8°C) and with 100 percent oversizing −15.6°C (compared to −16.1°C). The influence on the yearly average is consequently rather small when changing the level for the minimum flow from 20 to 40 percent.

FIELD STUDY

To investigate the theories in practice, field studies has been performed in a multi-dwelling building containing 20 flats. The radiator system in the building is oversized and the original temperature programme, 80/60°C, is adjusted to approximately match a 55/45°C programme.

The aim with the field experiments, apart from verifying the theories, is to develop a method for finding the minimum primary return temperature. The method can later on be used for developing an adaptive control algorithm.

The experiments are performed on a conventional DH substation consisting of a domestic hot water circuit and a radiator circuit.

A reduced radiator circulation flow rate means a reduced heat supply. To prevent this, the experiment starts by locking the control valve, which regulates the heat supply to the radiator circuit, in its current position. By locking the primary control valve the primary flow rate can be considered to be constant. Therefore, the transferred heat only depends on changes in the primary return temperature, which are small compared to the total temperature drop. As shown in the previous section, the return temperature is depending on the secondary circulation flow rate.

Obviously, both primary differential pressure as well as primary supply temperature can vary, even if these variations generally are quite slow. If needed, the primary flow can be adjusted to compensate for a changed differential pressure. In case of large variations of the primary differential pressure and/or supply temperature, the test will have to be restarted later.

Another problem is how to measure the heat supply to the radiator circuit, if there is no secondary energy meter (which normally is not the case). The method used here was to temporarily close the control valve to the domestic hot water circuit. Then, the primary flow rate to the radiator HEX is registered on the flow meter of the primary heat meter belonging to the substation. With temperature measurements on supply and return pipes on both primary and secondary side, both heat supply and secondary circulation flow rate can be calculated from the energy balance:

$$\dot{Q}_{\text{rad}} = \dot{m}_p \cdot c_p \cdot (T_{ps} - T_{pr}) = \dot{m}_s \cdot c_p \cdot (T_{ss} - T_{sr})$$  \hspace{1cm} (6)

This procedure is repeated at regular intervals during the test.

Test 1

During Test 1, the outdoor temperature was about 7.5°C, the heat load 33 kW and the primary
supply temperature varied from 87 to 90°C. The secondary flow was adjusted using a shut-off valve located after the circulation pump. The result from the test is shown in Figure 5.

Figure 5 Test 1. Decrease of the primary return temperature at reduced circulation flow rate.

The circulation flow was decreased in three steps, beginning at 10:40. Each flow change results in a sudden increase of the outgoing, secondary temperature. The secondary return temperature remains constant for a couple of minutes, due to transportation times, after which it begins to slowly decrease since the temperature drop in the radiators increases. At first, the primary return temperature increases a little, and then starts to decrease along with the secondary return temperature. The small increase depends on poor heat transfer in the HEX, which sets in immediately, while the following decrease depends on the increased secondary temperature difference, which changes more slowly depending on thermal inertia and transportation times in the radiator system.

The difference between the primary and the secondary return temperature increases when the circulation flow becomes lower, because of the deteriorated heat transfer.

The circulation flow was reduced by 17, 43 and 64 percent, respectively, during the test and resulted in a lowered primary return temperature; 2.5°C at the most, see Table 2.

### Table 2 Results from Test 1. Decrease of the primary return temperature with lowered circulation flow rate.

<table>
<thead>
<tr>
<th>(m_{\text{red}}) [%]</th>
<th>(T_{\text{ss}})</th>
<th>(T_{\text{sr}})</th>
<th>(\Delta T_{\text{ss}})</th>
<th>(\Delta T_{\text{pr}})</th>
<th>Time to steady state</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>43.1</td>
<td>35.7</td>
<td>7.4</td>
<td>36.2</td>
<td>0</td>
</tr>
<tr>
<td>83</td>
<td>44.1</td>
<td>35.3</td>
<td>8.8</td>
<td>35.8</td>
<td>-0.4</td>
</tr>
<tr>
<td>57</td>
<td>47.0</td>
<td>34.2</td>
<td>12.8</td>
<td>34.9</td>
<td>-1.3</td>
</tr>
<tr>
<td>36</td>
<td>52.8</td>
<td>32.4</td>
<td>20.4</td>
<td>33.6</td>
<td>-2.6</td>
</tr>
</tbody>
</table>

The last column indicates the time it takes to achieve stable conditions in the system. As seen, it takes some time to find an optimum, especially when the flow rate is low. This means that there is a risk for significant variations in primary differential pressure and supply temperature.

### Test 2

In the second test, the idea was to speed up the optimisation by utilising the fact that the secondary return temperature will decrease if the flow is decreased and the heat supply is constant. Taking this into account, one does not have to await a stationary secondary return temperature, but only long enough to see if the primary return temperature is decreasing. If so, the secondary flow can be further decreased.

The outdoor temperature during Test 2 was 7.3 ± 0.2°C, the heat supply was 30.7 kW and the primary supply temperature was 83.9 ± 0.1°C. The flow was reduced by variation of the rotation speed on the front panel of the pump. Some additional throttling using a shut-off valve was required to achieve a flow that was small enough. The result of the test is shown in Figure 6.

Figure 6 Test 2. Decrease of the primary return temperature when the circulation flow is reduced in shorter time intervals.
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The most obvious difference compared with Test 1 is that both the primary and secondary return temperature decrease continuously. A definite determination of the lowest primary return temperature will require the radiator circuit to stabilise. If the primary return temperature should increase after a flow reduction, the optimal operational point has been missed and the flow needs to be increased again.

DISCUSSION AND FUTURE WORK

The presented results show good possibilities to improve the cooling of primary water by optimising the radiator circulation flow and supply temperature for all heat loads.

For a practical application, the rotation speed of the pump and the supply temperature set-point can be adjusted on-line by a modified algorithm in the radiator controller.

An adaptive control algorithm also gives the possibility to identify a changed optimum. For example, a lowered primary supply temperature (which is very beneficial for the DH system if possible) can have a negative influence on the primary return temperature in a low flow radiator system. In such a case, it is desirable if the controller can identify the new optimum. Other factors affecting the most efficient operation of the system is for example fouling of the HEX or changed heat losses from the building.

To be able to establish a concrete application, more field tests in buildings with various degrees of oversizing, and at different outdoor temperatures, needs to be performed.

Since automation is used in most buildings today, more sophisticated control is possible to implement.

Another important conclusion is that the potential for the reduction in the primary return temperature can be even larger if the HEX is prolonged. When replacing or making a new installation of a HEX this could be taken into account.

ACKNOWLEDGEMENTS

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NOMENCLATURE

Abbreviations

DOT Design outdoor temperature
DH District heating
HEX HEX

Variables

\( c_p \) Heat capacity, J/kgK
\( \text{LMTD} \) Logarithmic mean temperature, °C
\( k \) Overall heat transfer coefficient, W/m²K
\( K \) Heat transfer constant, W/K
\( m \) Mass flow, kg/s
\( m_\text{rad} \) Radiator exponent, -, also mass flow
\( n \) HEX exponent, -
\( Q \) Heat flow, kW
\( T \) Temperature, °C

Subscripts

0 Design condition
i Indoor
p Primary (side)
rad Radiator (system)
s Secondary (side)

REFERENCES

OBSTACLES FOR NATURAL CIRCULATION IN HEATING SYSTEMS, CONNECTED TO DISTRICT HEATING VIA HEAT EXCHANGERS, DURING A POWER FAILURE

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ABSTRACT
The largest threat during a power failure of long duration is interrupted space heating, both in residential buildings and within sensitive public activities. Almost all heating systems are dependent on electricity, not only electric heating systems. Thus, hydronic heating systems need electricity for pump operation, control equipment, burners etc. Since district heating (DH) is a market-dominating type of heating method in Scandinavia (with almost 90 per cent of the heat market for multi-dwelling buildings in Sweden) it is of great importance to investigate the potential for buildings connected to DH to receive heat during an electric power failure.

In Sweden, heat from the DH water is transferred to the space heating radiator system via a heat exchanger (HEX). During a power failure the pump within the building, used for water circulation in the radiator system, as well as the control valve for controlling the DH flow, will be out of order.

In previous papers, results from field studies and simulations have shown that a significant amount of the original heat load in a building remains during a power failure. The phenomenon that makes this possible is natural circulation, a mechanism that was used for circulation in old radiator systems.

A modern heating system has several obstacles for natural circulation to arise. In this paper, problems with very high and/or long buildings, 1-pipe systems, by-pass connections, and reversed HEXs (installed upside-down) are analysed.

Keywords: District heating, Power failure, Space heating system, Natural circulation, Field study

INTRODUCTION
During a large scale power failure a lot of important functions in a modern society are affected. Heat supply is one important function during harsh weather conditions. Almost all heating systems, not only electric heating systems, are dependent on electricity in order to operate. Electricity is used for control equipment and for distribution of water in the heating system. These devices will of course not be able to work during a power failure.

District heating (DH) is the dominating heating system in Scandinavia, covering about 50% of the total heat market in Sweden (86% for multi-dwelling buildings, 70% for non residential buildings and 10% for one- and two-dwelling buildings) [4]. Buildings connected to the DH network in Sweden are connected via a heat exchanger (HEX), so-called indirect connection. This paper will also solely be focusing on indirect DH connections and no conclusions regarding the upholding of heat supplies during power failures with direct connections will therefore be made. However, in many countries direct connections are common ([5]) and to comment upon this fact, one must keep in mind that the use of HEXs is a definite obstacle for the heat transfer between the DH network and the secondary systems when no electricity is available. In this sense, the paper deals with the "worst case" and direct connections are left to future work.

In an indirectly connected building, electricity is used for controlling the heat output to the building by controlling the DH flow through the HEX and for pumps for distributing the water in the secondary system to the radiators. If the power supply fails, the circulation pump will stop and the control valve for the radiator system will stop in its current position, allowing for the same DH flow to pass through the HEX, provided that the DH network still is in operation.

In very old radiator systems the distribution was not dependent on a pump, but on the density differences between hot and cold water and the height of the system, so-called natural circulation. Characteristic of these systems are little flow resistance and a high secondary supply temperature to the radiator system. In modern heating systems, designed for pump operation, there are many components causing additional pressure losses such as HEX, balancing valves, much smaller pipe dimensions etc. Nevertheless, as demonstrated in previous papers ([1], [2]) the potential for natural circulation in a modern hydronic heating system connected to DH is not negligible. The potential for natural circulation depends not only on the type of heating system and its components, but also on the height and the length of the building as will be shown in this paper.

The heat production in a DH network is sometimes incorporated in a combined heat and power, CHP, station, which means that power and heat is generated in the same unit. In a CHP station, the DH network is used as a heat sink for the power production and many CHP stations have no other available heat sink.

To be able to establish island operation, which means local production and utilisation of electricity...
during a large-scale power failure on the national power grid, the CHP station will still need cooling for its operation. To fulfill this demand during island operation, when only limited supplies of electricity are available, the buildings connected to the DH network must be able to receive heat.

Apart from giving possibilities for island operation, the society as a whole can benefit if evacuations of citizens can be avoided or delayed during a long power failure during harsh weather conditions.

Objective of the study
In areas were DH has a large market share, the possibility to uphold heat supplies during a power failure of long duration is of great value for the society. The overall objective with the project is to secure heat supplies during a large scale power failure. The objective of this paper is to investigate obstacles for natural circulation to arise in space heating systems, originally designed for pump circulation, without electric power.

HEATING SYSTEMS CONNECTED TO DH
In a DH-connected building, the DH is used mainly for provision of domestic hot water and space heating. Space heat can be distributed by a hydronic radiator system and, especially in public buildings, via a forced ventilation system. Heat is transferred from the DH network (primary side) to the heating systems (secondary side) in the DH substation. In this work we have been focusing on so-called indirect DH connection which is the prevalent method in Sweden. This means that the DH system and the heating system are hydraulically separated by a HEX. Fig. 1 below shows an overview of a simple substation with a domestic hot water (DHW) circuit and a radiator circuit.

The substation in the picture is a so-called parallel coupled substation. Another very common design is two-stage connection, where cascading of the HEXs is employed to lower the primary return temperature. If the building has a ventilation system with forced airflows, heat is required to the air handling units. There are various ways to connect these units. One is to have an additional circuit connected in parallel to the DHW and radiator circuits, see Fig. 2.

![Fig. 1 Overview of a DH substation with a DHW and radiator circuit.](image1)

![Fig. 2 Substation with a ventilation circuit connected in parallel with DHW and radiator circuits.](image2)

![Fig. 3 HW circuit with a by-pass connection.](image3)

Another common variant is to combine the hot water to the radiators and air handling units in one circuit, often termed hot water (HW). Because the radiators and air handling units have different demands regarding temperature levels, by-pass connections are used, both for the radiator and ventilation circuit. The by-pass allows the secondary circuits to operate at individually lower temperature and pressure levels. Fig. 3 below shows a HW circuit with a common type of by-pass connection.

In most buildings the radiator system represents the largest part of the space heating supply, and in almost all residential buildings for the whole space heating supply. We will therefore mainly be focusing on the radiator system. Besides, all fans operating in the ventilation system will stop without power. Although, the by-pass connections are an essential part in the system and will be dealt with further on.

Fig. 4 below shows a simplified picture of a building with a space heating system connected to
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DH. DHW and possible forced ventilation have been omitted.

Tout

Tpr

Tps

Tss

Tsr

h

DH Sub-

station

Controller

pump

DH grid

Fig. 4 Building with a hydronic radiator system connected to DH.

The heat is transferred from the HEX via a piping system to the radiators. Normally, a 2-pipe system is used, i.e., one supply and one return pipe, which means that all radiators are connected in parallel. However, during the 60s and 70s, when a large number of residential buildings were built in Sweden, a lot of systems were built with a 1-pipe system, where the radiators in one or more flats are connected in series.

Traditional control of heat supply is based on variation of the supply temperature to the radiators, depending on the outdoor temperature. The supply temperature set-point is adjusted to compensate for the buildings’ thermal inertia. The requested supply temperature is obtained by controlling the DH flow through the HEX using a control valve, typically manoeuvred by an electric actuator.

Assuming that the DH network is still in operation during a power failure, the heat supply itself is not a problem (as would be the case with electrical heating, a heat pump or a boiler). However, all pumps, fans and control equipment need electricity to be able to distribute the heat in the building. The circulation pump in the system will stop. When the control equipment fails, the actuators will not receive any control signals and will in general stop in its current position. However, actuators in tap water systems are often equipped with a spring-return mechanism to avoid the risk of scalding from extremely hot tap water. Dampers in air handlers are generally equipped with a spring-return mechanism to avoid freezing. In space heating systems, however, spring-return is not used because it involves a higher cost and is not required. If the DH network is in operation, this means that there will still be a flow through the HEX. The question is whether any heat can be transferred into the building.

NATURAL CIRCULATION

This section will describe the mechanism for natural circulation and present results from field studies and computer simulations.

In parallel to field studies a theoretical computer model, of modern buildings operating with natural circulation during a power failure, has been developed. Results from computer simulations, theoretical relations and resemblance between simulated results and field studies are presented in detail in previous papers ([1] and [2]).

Mechanisms

Natural circulation is a well-known phenomenon, which occurs due to the density difference between hot and cold water. Very old heating systems were designed for natural circulation with low flow resistance in pipes and in the heating source. Fig. 5 shows a heating system designed for natural circulation (to the left in the picture) and a system designed for pump circulation (to the right).

Note that there is a slight inclination of the horizontal pipes in the system built for natural circulation. This helps to distribute heat in horizontal direction.

The differential pressure that causes natural circulation is, as mentioned before, dependent on the density difference between secondary supply and return temperature, and the height of the system, according to Eq.(1):

$$\Delta p = g \cdot h \cdot (\rho(T_{ss}) - \rho(T_{sr}))$$

(1)

A modern heating system has, as already mentioned, additional pressure losses. However, Eq.(1) is still applicable. If DH water is passing through the HEX during a power failure, the
temperature in the HEX will be substantially increased on the secondary side, since the circulation pump no longer is in operation. The increased temperature leads to an increased temperature difference in the secondary system. In combination with the height of the substation a differential pressure will arise, possible to cause a circulation. Fig. 6 below shows the result from a field experiment. The upper diagram shows temperature levels in the HEX, blue lines indicate the primary side and red lines indicate the secondary side. Solid lines are used for supply and dashed lines are used for return temperatures. The diagram in the middle shows the outdoor temperature and the lower diagram shows relative heat output (red) and secondary circulation flow (blue). The “power failure” begins at 9:40.

Fig. 6 Field experiment with natural circulation.

When the pump stops, the flow decreases which causes the secondary supply temperature to rise to almost the same level as the incoming DH water. Since the secondary temperature difference is large, the heat output is about 90% even though the secondary mass flow is reduced with more than 80%.

The secondary temperature difference is of great importance to the potential for natural circulation. Therefore, it is possible for the DH company to increase the primary supply temperature in the DH network and thereby increase the heat output. The influence of a changed primary supply temperature is discussed in [1].

In total, 14 different objects have been tested for natural circulation, including one- and multi-dwelling buildings, schools and nursing homes. Almost all buildings will receive a considerable amount of heat by means of natural circulation. However, as seen in Fig. 7, the relative heat output varies quite a lot between the objects, depending on the conditions in each system.

Fig. 7 Buildings tested for power failure. The column shows the heat supply (in relation to the initial) that was achieved during the test.

Limitations

There are several limitations for the potential for natural circulation in a modern heating system. A major difference between pump circulation and natural circulation in a modern heating system is that during natural circulation the differential pressure from the circulation pump is substituted by several pressure differentials from virtual pumps, each based on the temperature difference at its location in the heating system, see Fig. 8.

In the figure the circulation pump is substituted by one virtual pump in the horizontal distribution, based on the temperature difference of the incoming and outgoing secondary water and the height of the horizontal system \( h_0 \) which basically is the height of the substation [6]. A virtual pump is also found in each riser, provided that there is a temperature difference between supply and return pipe. The
The height of the risers \((h_1)\) determines the differential pressure. Naturally, these virtual pumps are always present, also during pump operation. However, since the pressure differential from the real pump is significantly higher (at least ten times higher, generally more) than the pressure differential due to density differences, the influence of this effect is generally negligible.

Due to the fact that the horizontal distribution has a smaller “pump” (because of the lower height) than the risers, it is possible that the natural circulation flow in horizontal direction will not reach all risers.

To study the influence of the different heights \((h_0\) and \(h_1)\) it is convenient to handle the system as a circuit diagram. Fig. 9 shows the circuit based on a simplified system with four risers. Each valve in the circuit is labelled with a \(k_v\) value and is equivalent to the pressure losses in pipes, radiators and radiator valves, balancing valves and HEX. The differential pressures emanating from temperature differences are symbolised by pumps.

![Circuit Diagram](image)

Fig. 9 A radiator system represented as a circuit diagram.

Now we use the well-known relation, applicable for turbulent flows:

\[
\Delta p = \left(\frac{V}{k_v}\right)^2
\]

(2)

Note that even for natural circulation, the flow can generally be considered as turbulent. For the circuit, an equation system can be set up, and from this we can find the different flows \((V_0, V_1, V_2, V_3\) and \(V_4)\) for different values on the pressure differentials and the \(k_v\) values. Using realistic parameter values (corresponding to the system shown in Fig. 6), we get the result shown in the first diagram of Fig. 10. The grey bars show the relative flow in each riser at pump operation \((V_0\) is the total flow and hence it is 100%). The black bars show the corresponding flows during natural circulation. The textbox indicates that we assume the risers to be five times as high as the substation and that we have a temperature difference, and hence a pressure differential, in all risers. If we look at the second diagram (upper right) the conditions are slightly changed: the height ratio is the same, but now we assume that the hot water temperature typical for natural circulation has not reached the last riser (which is due to the insufficient differential pressure in the horizontal distribution circuit). Accordingly, this riser receives a significantly lower flow. In the last diagram, the pressure conditions are the same as in the previous, but the height ratio is changed. We now assume the risers to be ten times higher than the substation. The result is that we end up with a negative flow in the last riser.

![Diagram](image)

Fig. 10 Relative circulation flows for different values of \(h_0 / h_1\) and \(\Delta p_4\). Grey bars correspond to pump circulation and black bars correspond to natural circulation.

The fact that the flow might change direction in some risers far from the substation was documented in one of the studied objects. In Fig. 11 we see supply and return temperatures on six risers situated around the point in the system beyond which the natural circulation did not reach. The house was an older ten-storied residential building. When the “power failure” begins around 9:30, all risers at first receive a higher temperature. However, later on we see that the return temperature becomes higher than the supply temperature in these risers, indicating a flow in negative direction.
Knowing that we might get a negative flow in some risers, one can wonder what the consequence will be. The negative flow in itself is hardly a problem. However, the results show that in some buildings, although the natural circulation is working well in most parts of the building, others might not receive any heat at all. This fact must be kept in mind, especially when dealing with high and/or horizontally extended systems.

As mentioned earlier, some heating systems are constructed as 1-pipe systems, which was popular during the 60s and 70s in Sweden. 1-pipe systems are typically found in very large buildings or with more than one building integrated in the same radiator system. Several radiators, sometimes ten or more, are connected in series and the systems are characterised by substantial pressure drops. An overview of a test in such a system is showed in Fig. 12, where red areas indicate where natural circulation was established.

As shown in the figure, the distribution pipes from the substation to the houses are almost 100 metres each. Still, the flow manages to reach both houses and approximately half of the risers. Fig. 13 shows the supply and return temperatures in the radiator system measured at the substation and at the entrance to each of the two houses. We see that it takes about an hour for the flow to transport through the distribution pipes, and when a flow is stabilised, the temperature loss amounts to 7-10°C.

It is not entirely obvious whether it is the 1-pipe system or the horizontally extended system, which constitutes the largest limit for natural circulation. The heat load estimates to about 50% and reaches approximately half the system, i.e., the heat load in one part of the system is sufficient once the circulation reaches this part. Because the circulation does not reach all parts of the system, it is likely that the effect earlier described, that the system must not
be too high or long, that mainly inhibits the circulation.

Since the differential pressure is limited without electricity the system is sensitive to outer disturbances such as hydraulic short circuits. These could occur in systems when a by-pass connection is used. By-pass connections are commonly used for reducing the HW circuit temperature. There are several different types of by-pass connections. The most commonly used type in DH-connected systems is shown in Fig. 14.

![Fig. 14 Overview of a by-pass connection.](image)

When power fails, the pump in the ventilation/radiator circuit stops. The control valve stops in its position allowing HW to reach the circuit. Since the circuit has a larger height, the differential pressure causing natural circulation is bigger than in the HW circuit. This might cause an opening of the check valve allowing return water to mix with supply water. This results in a reduced supply temperature to the ventilation/radiator circuit. The result from a field experiment with a by-pass connection during a power failure is shown in Fig. 15.

![Fig. 15 Supply (solid lines) and return (dashed lines) temperatures at the substation and at a by-pass connection.](image)

As can be seen in the figure the temperature after the bypass valve is significantly lower than the incoming HW temperature before the by-pass connection. Still, the temperature leaving the by-pass connection is sufficient for a substantial natural circulation to arise.

When assessing the potential for natural circulation in a system with by-pass connections, one can expect that they limit the circulation. It is desirable if one can make it possible to close the check valves, manually or automatically.

Normally the primary and the secondary supply pipes are connected at the top of the HEX. During the field studies, a type of substation was discovered that had the supply pipes connected at the bottom. This has no effect on the normal operation of the substation. However, in case of a power failure, the water on the secondary side of the HEX becomes very hot. Without the pump in operation, the hot water will rise and leave the HEX at the top, resulting in a changed flow direction. Now, the HEX will work as a co-current HEX instead of a counter-current HEX. See Fig. 16 below.

![Fig. 16 Common outline of a radiator HEX (left) and the reversed type (right).](image)

The consequence of having this type of connection was studied in a field experiment, see Fig. 17.

![Fig. 17 Result from a natural circulation test in a system with a reversed radiator HEX. See Fig. 6 for notations.](image)

When the HEX is working as a co-current HEX the secondary supply temperature is limited by the primary return temperature (instead of the primary
supply temperature). This means that the secondary temperature difference, and consequently the pressure difference, is limited. Also, the secondary flow has changed its direction, which most likely will have a negative influence on the heat output in the radiators.

Another disadvantage is that the primary return temperature becomes very high. This connection type is not to recommend due to its limited potential for natural circulation and its high return temperature during a power failure.

DISCUSSION

Although almost all hydronic heating systems today are designed to operate using a circulation pump, natural circulation is likely to arise to some extent in most systems connected to DH. This fact is of great interest for DH companies as well as for municipalities and owners of property.

A modern heating system has several obstacles for natural circulation to be able to develop. In this paper, problems which occur in very high and/or long buildings, 1-pipe systems, by-pass connections, and reversed HEXs (installed upside-down) have been shown.

It is concluded that even though heat will not be distributed evenly in a whole building, the parts that do receive heat, most likely will receive enough.

With the lower temperature levels in the heating system that are received from by-pass connections and a reversed HEX, the potential heat output is significantly decreased.

When assessing the possibilities for a specific building to receive DH during a power failure utilising natural circulation, the obstacles discussed in this paper should be considered.

To facilitate for a heat load as large as possible during a power failure, some pitfalls should be avoided. By avoiding reversed HEXs and by-pass connections in radiator systems, as long as possible, this can be fulfilled. When by-pass connections are used, it is desirable if the check valve can be closed, manually or automatically, during a power failure in order to facilitate natural circulation.

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NOMENCLATURE

Abbreviations
CV Control valve
DH District Heating
DHW Domestic Hot Water
HEX HEX
HW Hot Water circuit
Rad Radiator circuit

Variables
\( g \) Gravity force, m/s^2
\( h \) Height, m
\( k_v \) Valve capacity, m^3/(s·bar^{1/2})
\( m \) Massflow, kg/s
\( p \) Pressure, Pa
\( Q \) Heat flow, W
\( T \) Temperature, °C
\( \dot{V} \) Volume flow, m^3/s
\( \rho \) Density, kg/m^3

Subscripts
\( o \) Outside
\( p \) Primary
\( r \) Return
\( s \) Secondary, supply

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MODELLING SPACE HEATING SYSTEMS CONNECTED TO DISTRICT HEATING IN CASE OF ELECTRIC POWER FAILURE

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ABSTRACT
Since district heating (DH) is the dominating heating system in Scandinavia, and fairly common in large parts of Europe, it is of vital interest to study the possibility for buildings connected to a DH network to receive heat during an electric power failure. Our studies have proved it possible to achieve natural circulation in space heating systems indirectly connected to DH if the DH network operation can be maintained.

Natural circulation in modern heating systems has been simulated. The model shows good resemblance with field studies. By using a model the influence of different parameters can be studied, e.g., a changed DH supply temperature and different outdoor conditions.

INTRODUCTION
A large-scale power failure affects many vital functions of society, e.g., space heating. Obviously, heating systems using electricity (either directly or via a heat pump) cannot operate at all, but systems using a boiler (oil, natural gas, pellets, etc.) will generally not work either since electricity is required for the operation of burners and control equipment.

District heating (DH) is common in many countries and it is the dominating heating system in, e.g., Denmark, Finland and Sweden. Therefore, it is of vital interest to study what can be expected to happen in buildings connected to DH in case of a power failure, assuming that the production of DH can be maintained.

Hydronic radiator systems in modern buildings are fitted with circulation pumps that will stop when electricity supply fails. Consequently, the heating of buildings connected to a DH network are generally assumed to stop functioning in such an event. Nevertheless, our recent studies have proved that in many cases a substantial natural circulation effect caused by an increased water density differential takes place in many cases.

The major power failures that have occurred in recent years have led to an increased focus on the possibility of local production and distribution of electric power during a breakdown of the national power grid, so-called ‘island operation’. In order for the production of electricity in combined heat and power (CHP) stations to be maintained, it is necessary that excess heat continues to be removed from the power generating plant. If it is possible to use the DH network as a heat sink, i.e., if buildings connected to the DH network carry on consuming heat energy, provisions for additional cooling of the plant may not be necessary. One must keep in mind that, even if an island power grid were established, the access to power would generally be strictly limited and possibly directed to prioritised users (e.g., hospitals, authorities).

For our society, it is essential that building heat supplies be maintained, especially in the event of a power failure of long duration during harsh weather conditions. If evacuations of people from buildings can be avoided, or at least delayed, this will help protect especially elderly people and persons in need of health care from risky exposure to low air temperatures.

Because of the concern for these matters from DH utilities as well as from authorities and owners of property, the present study was carried out, with the aim at finding out what could be expected to happen in buildings connected to the DH network, in the event of a severe power failure.

The objective of the overall study was to investigate what can be expected to happen in space heating systems connected to DH when a power failure occurs. The study is limited to so-called indirect connection, i.e., that the DH system and the building heating system are hydraulically separated by heat exchangers (HEX), which in this context must be considered as a worst-case scenario compared to direct connection.

We have found that natural circulation can arise in modern space heating systems; most buildings can achieve a space heat supply corresponding to 40-80 per cent of the amount prior to the interruption, at low outdoor temperature [4]. Natural circulation was used many years ago, before pumps were introduced in space heating systems, and is based on the difference in density between hot and cold water. I.e., hot water from the heat source rises in the vertical supply pipes. In reverse, when the water is cooled off in the radiators, the cold water descends back to the heat source. With natural circulation in a modern system, the flow becomes significantly smaller and, therefore, very hot in the HEX. With a high supply tem-
perature to the radiators and a high temperature drop in the system, the heat supply becomes surprisingly high, despite the low circulation flow rate.

Computer simulations are a useful tool to complement field experiments in the process of estimating the possibilities for natural circulation in different types of heating systems and buildings.

**OBJECTIVE**

To be able to study the influence of different parameters that might be difficult to capture in reality, e.g., very low outdoor temperatures and the possible gain from an increased DH supply temperature, the field studies have been complemented with computer simulations using models built with the software Matlab and the associated toolbox Simulink.

The objective of the paper is to simulate how natural circulation works in modern space heating systems at differing outer conditions. The simulations should be seen as an isolated project in the sense that the ambition was not to construct a general model, available to anyone, but rather to construct a simple model designed to complement our field studies. Furthermore, because of our limited skills in, and access to, commercial buildings simulation software, previously developed models for DH purposes was used and further developed.

**SPACE HEATING SYSTEMS CONNECTED TO DH**

Figure 1 below describes a hydronic radiator system with an indirect connection to a DH network. The water from the DH network is led into a HEX where the radiator water is heated. The secondary supply temperature, $T_{ss}$, is regulated by a controller which in turn regulates the DH flow passing through the HEX. The set point for $T_{ss}$ is based on the current outdoor temperature and the building’s time constant. An electric pump achieves the circulation in the radiator system. In order to receive proper indoor temperature in the whole building, valves are used to balance the flow between risers and radiators in different parts of the system.

Figure 1: A building with space heating system connected to a DH network.

**COMPUTER MODELLING**

The building model is based on existing models of HEX, control equipment, actuators, valves, connection pipes, radiators and building. The theory and function of these components have been described in detail by a number of authors, for example [1], [2] and [6].

In this work, these components have been put together in order to constitute a complete building model with DH substation, space heating system and building shell. To be able to meet the objective of this work, the model has also been modified on several points. The space heating system has been extended to comprise four risers and three storeys, making it possible to study the heat distribution in the building during natural circulation. The flow distribution with pump operation is built on a method based on an analogy to Kirchoff’s circuit laws. With natural circulation, the problem must however be attacked in a slightly different way, which will be described later on.

Some assumptions have to be made in order to limit the complexity of the model and the computational time. One assumption is that there is no heat transfer between the flats. The consequence of the assumption is that if the radiator flow is unbalanced the indoor temperature in the flats will not be accurate because heat conduction through the walls between the flats is neglected. However, the average temperature in the building will still be correct.

The overall structure of the complete model is shown in Figure 2 below.
NORMAL OPERATION

To begin with, we look at the model when normal (pump) operation is simulated. However, most parts work in the same way in both cases.

Heat exchanger

The first step in the energy transfer from the DH network to the building takes place in the DH substation where heat is transferred via a HEX. A control valve adjusts the DH flow in order to achieve the correct outgoing temperature on the secondary side of the HEX, i.e., the radiator supply temperature. A traditional way to handle the dynamic thermal behaviour of the HEX is to divide it into a number of sections. For each section, energy balances can be stated for both primary and secondary side flows, and for the wall separating them. After differentiating, the following equations are obtained:

\[
\frac{\partial}{\partial t}(T_{s,\text{out}}) = \frac{1}{m_{c,p,s}} \left[ m_{c,p,s}(T_{s,\text{in}} - T_{s,\text{out}}) - \alpha_s A \left( \frac{T_{s,\text{in}} + T_{s,\text{out}}}{2} - T_{\text{wall}} \right) \right]
\]

\[
\frac{\partial}{\partial t}(T_{p,\text{out}}) = \frac{1}{m_{c,p,p}} \left[ m_{c,p,p}(T_{p,\text{in}} - T_{p,\text{out}}) - \alpha_{p,\text{r}} A \left( \frac{T_{p,\text{in}} + T_{p,\text{out}}}{2} - T_{\text{wall}} \right) \right]
\]

\[
\frac{\partial}{\partial t}(T_{\text{wall}}) = \frac{A}{m_{\text{wall}} c_{\text{wall}}} \left[ \alpha_{p} \left( \frac{T_{p,\text{in}} + T_{p,\text{out}}}{2} - T_{\text{wall}} \right) - \alpha_s \left( \frac{T_{s,\text{in}} + T_{s,\text{out}}}{2} - T_{\text{wall}} \right) \right]
\]

The temperature profile is assumed linear, while the theoretically correct profile is logarithmic. The logarithmic mean temperature difference, LMTD, is defined as:

\[
LMTD = \frac{(T_{p,s} - T_{s,s}) - (T_{p,r} - T_{s,r})}{\ln \left( \frac{T_{p,s} - T_{s,s}}{T_{p,r} - T_{s,r}} \right)}
\]

The advantage of using an arithmetic mean temperature difference is that the heat transfer can be directed in both ways, i.e., from primary to secondary side and vice versa. Such situations can occur for short periods in the space heating HEX. This means that we must use a sufficient number of sections in the model. On the other hand, more sections will increase the computational time. A suitable choice is to divide the HEX into 3-5 sections, [7].

The method involves a number of assumptions such as uniform temperature in each section, no conduction in the water flow direction or in the length direction of the HEX wall. The heat transfer coefficient, \( \alpha \), is approximated to be a function of the flow only, ignoring minor influence from temperature dependant quantities. The thermal resistance in the wall material can be ignored due to the thinness of the plate. All these assumptions ease the mathematical description, but investigations still have proved a good resemblance to real data. [1], [9].

Piping and heat distribution system

The piping system model includes three features, pressure drop, heat loss and time delay. The pressure drop due to friction in pipes, valves, radiators and HEX is essential when calculating the flows in the system. The heat loss is of minor interest at normal (pump) operation, while the time delay could be of some interest. However, when simulating natural circulation, all of these features become essential. The driving force from natural circulation is rather small, leading to a substantially smaller circulation flow and, consequently, a lower flow velocity. Especially when studying larger buildings, transportation times and heat losses can be considerable and are essential for the operation of the system.

The heat carrier from the HEX to the radiator is the circulating water in the system. The flow depends on the available pump head and the flow resistance in the system. We can assume wholly turbulent flows and limited temperature variations, which means that the relation between the volume flow and differential pressure in a component can be approximated as:

\[
\dot{V} = k_v \sqrt{\Delta p}
\]

The factor \( k_v \) describes the flow capacity of a component (to be precise, the flow capacity at 1 bar differential pressure). A \( k_v \) value can be calculated for all components, a pipe section, valve (which has a variable \( k_v \), value depending on the opening degree), HEX
or radiator, as long as the pressure loss for a specific flow is known.

For a system with many components (connected in parallel or series), equivalent $k_v$ values can be calculated from:

$$k_{v,eq,parallel} = \frac{1}{\sum_{i=1}^{N} k_{v,i}}$$

$$(6)$$

The same principles used in electric circuits resistance calculations can be used upon a hydronic heating system, see [6] and [3]. In this way, an equivalent $k_v$ value for the whole circuit can be found, see Figure 3.

Finally, after going through the entire system, we have only one equivalent $k_v$ value for the whole system, and equation (5) can be used to calculate the total circulation flow, $V$, in the system. Then, the flow in each part of the system can be calculated once again by going through the system, but now in the opposite direction. We know the available differential pressure for the first branch (after the pump) and the equivalent $k_v$ value and equation (5) gives us the flow through branch 1. We can then carry on by subtracting the pressure loss caused by branch 1 from the pump pressure and repeat the calculation for branch 2, and so on.

$$\dot{Q}_{rad} = \dot{m}_r \cdot c_{p,r} (T_{in} - T_{out})_{rad}$$

$$(8)$$

Note that $LMTD$ is raised to the exponent $n$. This is an approximation of the fact that only part of the heat transfer from the radiator is due to convection, the rest is due to radiation. The contribution from radiation (which normally amounts to 30-50 per cent of the heat transfer) is also a function of the temperature difference between the radiator’s surface and the surrounding walls. The complex relation, which also includes physical quantities, can be simplified by including the radiation in equation (7) by introducing the so-called radiator exponent, $n$ [8].

**Building**

A common method to model the dynamics of the building’s heat losses is described for example in [1] and [5]. The basic idea is more or less the same as with the HEX and the radiator. A section of the wall is treated as a homogenous material with a homogenous temperature described as:

$$\frac{\partial}{\partial t} (T_{w}) = \frac{1}{m_w c_{p,w}} [ \alpha_r (T_{rad} - T_w) - \alpha_w (T_{rad} - T_{in}) ]$$

$$(9)$$

To use only one section would be sufficient when modelling the operation of a space heating system during “normal” conditions or static calculations, i.e., where the transient course of the indoor air temperature is of minor interest.

However, if the heat supply is cut off (or substantially decreased) the indoor air temperature will drastically move towards the wall temperature. The model must therefore have a realistic approximation of the wall surface temperature (normally just a few degrees cooler than the indoor air).

By using three sections we obtain a good approximation of the wall temperature, see Figure 4. The two innermost sections are assumed to be made of concrete, which has a high conductivity but a large mass, and the outermost section is the insulation, which has a low conductivity but a small mass. Both materials are essential. The concrete will assure that we have an inside wall temperature relatively close to the indoor temperature and make sure that the building has
a realistic thermal inertia. The insulation will assure that we get the correct heat loss and temperature drop through the wall. The choice to use three sections is a compromise; more sections give higher accuracy but longer computational times.

To simulate natural circulation, the model is modified by including these “pumps”. Then, an equivalent $k_v$ value for the whole system cannot be calculated. Instead, the flow in each riser is calculated individually. The total flow in the system is equal to the sum of the riser flows.

At first sight, it may seem that natural circulation benefits from high risers (according to equation (12)). However, this need not be the case: the density difference of water means, that one can say that the system has a small virtual circulation pump at all points with a height and a temperature difference. This is illustrated by Figure 5.

Let us consider natural circulation in an extreme system that has a very large height difference at the HEX, situated in a low building with a small bottom area. This is a system with conditions similar to normal pump operation, with the main differential pressure arising from the substation. Conversely, we can imagine a system with a low driving height in the basement circuit while the risers are very high. The heat may then have difficulties to reach the whole system when risers with a large pressure differential tend to "suck" flow from subsequent risers.

**NATURAL CIRCULATION**

Many years ago, before pumps were introduced, heating systems were designed to operate with natural circulation. The differential pressure that drives the circulation can be derived from:

$$\Delta p_{\text{net}} = g \cdot h (\rho_r - \rho_i)$$  \hspace{1cm} (12)

The height difference, $h$, of the system is measured between the heat source (HEX) and the heat sink (radiator). The natural circulation force is present also in a pump system, but is negligible compared to the pump’s pressure head. When designing a natural circulation system, large pipe diameters must be used in order to minimize pressure drops. The question is how natural circulation works in a system designed for pump operation. Clearly, natural circulation does not work in single-storied buildings, a fact that has also been found during our study.

**Dynamic modelling of natural circulation**

As a first approach, the differential pressure from the pump can be substituted with a differential pressure calculated from equation (12), based on supply and return temperatures at the HEX and the system’s height. This is, however, a simplified model, since the differential pressure actually arises at every place in the system where there is a height and a temperature difference, i.e., risers and substation. When testing natural circulation in large buildings, it turns out that some risers, situated far from the HEX, might not obtain any circulation.
Even though we now deal with natural circulation, the flows are generally still turbulent. Once again, we use equation (5), and it is now possible to set up a system of equations for the whole circuit:

\[
\begin{align*}
\Delta p_{34} &= -\frac{1}{k_{v,34}} \left( \frac{1}{k_{v,3}^2} + \frac{1}{k_{v,4}^2} \right) V_3 + \Delta p_4 = \\
&= \Delta p_3 - \frac{1}{k_{v,3}^2} \cdot V_3 \\
\Delta p_{23} &= -\frac{1}{k_{v,23}} (V_2 + V_4) + \Delta p_{34} = \\
&= \Delta p_2 - \frac{1}{k_{v,2}^2} \cdot V_2 \\
\Delta p_{12} &= -\frac{1}{k_{v,12}} (V_1 + V_3 + V_4) + \Delta p_{23} = \\
&= \Delta p_1 - \frac{1}{k_{v,1}^2} \cdot V_1 \\
\Delta p_{12} &= \left( \frac{1}{k_{v,0}^2} + \frac{1}{k_{v,01}^2} \right) (V_1 + V_2 + V_3 + V_4) - \Delta p_0 = \\
&= \Delta p_1 - \frac{1}{k_{v,1}^2} \cdot V
\end{align*}
\]

(13)

The equation system can be transferred to the matrix form:

\[
\mathbf{A} \cdot \mathbf{V}^2 = \mathbf{b}
\]

where,

\[
\mathbf{A} = \begin{bmatrix} 0 & 0 & 1 & a_{44} \\ 0 & 1 & a_{23} & a_{24} \\ 1 & a_{32} & a_{33} & a_{34} \\ a_{41} & 1 & 1 & 1 \end{bmatrix},
\]

\[
a_{44} = -\frac{1}{k_{v,34}^2} + \frac{1}{k_{v,4}^2}, \quad a_{23} = -\frac{1}{k_{v,23}^2} + \frac{1}{k_{v,2}^2}, \quad a_{32} = -\frac{1}{k_{v,32}^2} + \frac{1}{k_{v,3}^2}, \quad a_{34} = -\frac{1}{k_{v,34}^2} + \frac{1}{k_{v,4}^2}, \quad a_{41} = 1 + \frac{1}{k_{v,0}^2} + \frac{1}{k_{v,01}^2},
\]

Equation (14) gives the different flows \((\dot{V}_0, \dot{V}_1, \dot{V}_2, \dot{V}_3, \dot{V}_4)\) for various differential pressures and \(k_v\) values. By using typical parameter values, we get the result shown in the first diagram in Figure 7. The gray bars show the relative flow at normal (pump) operation (the total flow, \(\dot{V}_0\), is 100 per cent). The black bars correspond to the flows at natural circulation. As indicated in the textbox, the risers are assumed to be five times as high as the HEX and we assume that there is a temperature difference, and consequently a pressure difference, at all risers. The natural circulation flow is approximately 20 per cent and evenly distributed in the system. In the next diagram (upper right), the height difference is assumed to be the same but now it is assumed that the heat front, typical for natural circulation, has not reached the last riser, which could be the case if the differential pressure in the horizontal distribution is not sufficient. Therefore, the last riser gets a much lower flow. In the last diagram, the pressure conditions are the same as in the previous diagram, but the height relation is changed. The risers are now assumed ten times as high as the HEX. The result is that the flow in the last riser becomes negative.

Figure 6 Simplified radiator system with natural circulation, presented as a circuit scheme.
The fact that the flow might change flow direction in some risers far away from the DH substation was documented in one of the tested objects. The building has 10 storeys and 100 flats and the substation is situated at one end of the building. The heat supply estimated to approximately 85 per cent but did not reach the farthest third of the building. The negative flow is in itself no problem, but it is important to know that in some buildings natural circulation functions perfectly well in some parts of the building while others do not get any heat at all. This should be kept in mind for buildings that are very high and/or horizontally extended. Our studies have shown that this factor is more important than the flow resistance in the system, e.g., if the system is old, or if it is a 1- or 2-pipe system.

SIMULATIONS

The dynamic model of natural circulation is not able to handle negative flows in the system. This would require a more advanced model. For the study below, sufficient precision is achieved with the dynamic model, i.e., that natural circulation is included in the model at every point in the system where there is a height difference. Should such a building be simulated, where negative flows occur, we might get convergence problems. However, this type of buildings represents a minor part of the building stock in Sweden, and in order to study the influence of the outdoor and the DH supply temperatures, it is not useful to extend the model. When estimating the heat supply, it is of less importance if the circulation flow rate in parts of a building is small but positive, or in fact negative.

Assumptions for the simulations

The supply temperature in the DH network is a function of the outdoor temperature. In the study the temperature profile for the network in Malmö is used for the simulations, see Figure 8.

Model evaluation

For evaluation of the model, a comparison between a field study and a simulation are made in Figure 9. The building is built in 1952, with 20 flats distributed on three floors. Before the time zero in the diagram, the operation is normal and circulation flow and heat output is set to 100 per cent. At time zero, power is cut off and the circulation flow decreases drastically. Therefore, the radiator supply temperature increases substantially. Finally, we end up with a substantially higher temperature drop in the space heating system, which leads to a rather high heat load even though the circulation flow is very small.

Assumptions for the simulations

The supply temperature in the DH network is a function of the outdoor temperature. In the study the temperature profile for the network in Malmö is used for the simulations, see Figure 8.
Parameter variation

In case of a power failure, the DH utility could possibly adjust the primary supply temperature level, which could enhance the natural circulation in the connected systems. In Figure 10, steady state results (the state after infinite time) from simulations with different primary supply temperatures are shown at different outdoor temperatures. In the upper diagram, the relative heat load is shown. The lower diagram shows the mean indoor temperature.

Figure 10 Variation of primary supply temperature at various outdoor temperatures at steady state conditions.

The figure shows that by increasing the primary supply temperature the relative heat load increases, especially for outdoor temperatures above −10°C. At low outdoor temperatures the effects of increasing the primary supply temperature to 120°C is small due to the already high supply temperature. The next diagram, Figure 11, shows the dynamic indoor temperature at three different outdoor temperatures.

Figure 11 Dynamic indoor temperature at different outdoor temperatures and for various primary supply temperatures.

The figure clearly shows the influence of the building’s thermal inertia. A limited heat supply means that an acceptable indoor temperature would be maintained for several days, in this case 16°C after four days with an outdoor temperature of −15°C.

Conclusions

A complete model of a building with a hydronic heating system connected to DH is built up to work properly both with, and without, electric power supply. Results from simulations and field studies have made it possible to assess how buildings connected to DH work during a power failure. The computer model shows good resemblance with field tests and gives possibilities to perform parameter variations, which is difficult to perform in field tests.

Among other things, the height and extension of a building have proven to be important for the distribution of natural circulation within the system. This knowledge has been confirmed by static calculations, but has not been included in the dynamic model.

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NOMENCLATURE

Variables:

- A: Area, m²
- cp: Specific heat capacity, J/kgK
- h: Height, m
- k: Flow capacity, kg/(s·Pa 1/2)
- LMTD: Logarithmic mean temp. diff., °C
- m: Mass, kg
- m: Mass flow, kg/s
- n: Radiator exponent
- p: Pressure, Pa
- Q: Heat flow, W
- T: Temperature, °C
- C: Radiator heat transfer const., W/m²K
- V: Volume flow, m³/s
- α: Heat transfer coeff., W/m²K
- ρ: Density, kg/m³

Subscripts:

- br: Branch
- eq: Equivalent
- exp: Experimental
- hor: Horizontal
- i: Indoor
- int: Internal
- N: Nbr of branches
- nat: Natural circulation
- o, out: Outdoor
- p: Primary
- r: Return
- rad: Radiator
- s: Secondary, supply
- sim: Simulated
- vent: Ventilation
- w: Wall
- ∞: Stationary values

REFERENCES


A TURBINE-DRIVEN CIRCULATION PUMP IN A DISTRICT HEATING SUBSTATION

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Abstract. The paper describes the idea of a circulation pump in the radiator system powered by a turbine placed on the primary side of a district heating (DH) substation. In this way, the pressure difference between the supply and return pipes is utilised to drive the circulation on the secondary (house-internal) side. The idea is to utilise the redundant differential pressure that exists in most DH substations (because of the minimum pressure difference that must be maintained everywhere in the network) to drive the turbine. There are two main ideas here; one is that this can serve as a fallback solution in order to ensure heat supply during a power failure. If only the DH provider can maintain the operation of the network by using backup power, customers will be able to receive heat. In a previous study, we showed that in many buildings between 40 and 80 percent of the heat supply can be maintained by natural circulation in the DH connected radiator systems. However, one cannot count on that natural circulation works satisfactorily in all buildings. The proposed turbine device could serve as a fallback arrangement in those buildings. The second idea is to examine whether the turbine pump device can operate continuously. Many substations have a redundant differential pressure which, when utilised in the turbine pump, can imply a saving of electrical energy. A prototype has been developed in co-operation with a pump manufacturer. It has been tested as well in laboratory as in a DH substation. The turbine pump proved to work as backup system in a DH connected radiator system (if the operation of the DH network is maintained) but further studies are needed to explore the opportunities for continuous operation. Since the flow ratio between primary and secondary side varies with the heat load, it may be difficult to use a turbine pump with direct connection from primary to secondary side. One should consider a hydraulic bypass of the turbine, possibly supplemented with an electrical connection between primary and secondary side through a generator and electric motor, preferably with a connection to the power grid.

Keywords: district heating, turbine-driven pump, secure heat supply

1. INTRODUCTION

This paper presents results from empirical tests of a prototype of a concept where the circulation pump in a radiator system is driven by a turbine, which in turn is driven by the differential pressure in a district heating (DH) network. The concept is an alternative, or complement, to the arrangement that is normally used with an indirect connection of a building to a DH network. Indirect connection refers to that there is a heat exchanger (HEX) providing hydraulic separation of the radiator circuit from the DH network.

Normally, the circulation pump in a radiator system is powered by an electric motor. The DH flow to the HEX is normally throttled by a control valve in series with the HEX, in which case one could say that a large part of the differential pressure (between the supply and return pipe) in the DH network is not used, as it will be under the proposed concept.

Obviously, the throttling does not mean that energy is lost in the sense of the first law of thermodynamics; the circulation pumps convert electrical energy to work, which in turn is converted to heat energy due to friction losses is pipes, heat exchangers, and valves. When control valves in substations throttle the flow, it does not cause energy to leave the system. However, it does imply a loss of exergy in the sense of the second law of thermodynamics, because useful work is converted to heat [1]. The concept means that less electricity, as a whole, needs to be added to the system, since the turbine pump implies a recovery of work, and an otherwise inevitable exergy loss can be reduced.

Originally, the idea was proposed 10 years ago, independently of each other, by R. Jonson in a Swedish patent application [3] and by S. Frederiksen, Lund University. The concept has been termed “Autonomous District Heating” and has the potential to both ensure the circulation during a power failure, and to save electricity by continuous operation of the circulation pump. The concept was previously presented at the 11th International Symposium of District Heating and Cooling 2008 in Reykjavik [2].

This paper presents results from empirical tests of a prototype based on the concept. The prototype has been manufactured by an industrial partner in consultation with us. They have tested the prototype in their laboratory, and we have tested it in a field study, where the prototype was placed in a building that is connected to the DH network in Gothenburg.

2. NATURAL CIRCULATION

In a recent project, together with the Swedish Energy Agency, the Swedish District Heating Association, two local real estate companies and the DH utility (operated by E.ON) in the town Malmö in Sweden, we studied the possibilities...
to maintain the heat supply during a power failure [4]. The work examined whether natural circulation can arise in the connected buildings, given that the operation of the DH network can be maintained. Several buildings were tested and the results have been surprisingly positive: in many buildings, between 40 and 80 percent of the heat supply can be maintained through natural circulation. The study however showed that one cannot assume that this works satisfactorily in all types of buildings. The proposed device could act as fallback arrangement in these buildings.

3. TURBINE DRIVEN CIRCULATION PUMP

Figure 1 shows the radiator system part of a DH substation with the proposed device in its simplest form, the turbine and the pump on a common shaft, here with the turbine in series with the radiator HEX.

The link between the turbine and the pump can be arranged in different ways. As in the figure, one can have a simple mechanical coupling, possibly with a gear. Another option would be to let the turbine drive a generator, which in turn supplies the pump with electrical energy. A hybrid solution is also possible, where the mechanical coupling is combined with an electric motor that also can function as generator. Some of the factors that determine which configuration is most appropriate are:

- Optimum speeds of turbine and pump shafts
- The differential pressure on the primary side vs. flow needs in the secondary side
- Transmission losses, if generator and motor are used
- Robustness
- Price

The potential for the turbine power to be sufficient to operate the circulation pump can be estimated by the following example. The total required efficiency of the turbine pump can be described as

$$\eta_{tot} = \eta_{turbine} \cdot \eta_{pump} = \frac{P_{shaft}}{P_{hydr, DH}} \cdot \frac{P_{hydr, DH}}{P_{shaft}} = \frac{(\dot{V} \cdot \Delta p)_{rad}}{(\dot{V} \cdot \Delta p)_{DH}}.$$  \hspace{1cm} (1)

The energy balance for the transferred energy in the radiator HEX

$$\dot{Q} = (\rho \cdot \dot{V} \cdot c_p \cdot \Delta T)_{DH} = (\rho \cdot \dot{V} \cdot c_p \cdot \Delta T)_{rad}$$  \hspace{1cm} (2)

can be simplified to

$$\frac{\dot{V}_{rad}}{\dot{V}_{DH}} = \frac{\Delta T_{DH}}{\Delta T_{rad}}.$$  \hspace{1cm} (3)

When inserted in the expression for the efficiency, we obtain
\[ \eta_{tot} = \frac{\Delta T_{DH}}{\Delta T_{in}} \cdot \frac{\Delta p_{val}}{\Delta p_{DH}} \] (4)

Let us assume a specific case where the incoming and outgoing DH temperatures are 100 and 45°C, respectively, and the temperature increases from 40 to 60°C in the radiator system. If we also assume that the differential pressure for the turbine on the primary side is 4 bars and the circulation pump provides a pressure increase of 0.3 bars, it means that the total efficiency must be:

\[ \eta_{tot} = \frac{(100 - 45)}{(60 - 40)} \cdot \frac{0.3}{4} \approx 21\% \] (5)

This could for example be achieved with a turbine efficiency of 30 per cent and a pump efficiency of 70 per cent according to:

\[ \eta_{tot} = \eta_{turbine} \cdot \eta_{pump} = 0.7 \cdot 0.3 = 21\% \] (6)

The example shows that the device can function even when conditions vary greatly at different operating cases. We will discuss this further later on.

3.1. Pumps as turbines (PAT)

It may seem expensive to install a water turbine in each DH substation. However, it appears that it could be possible to use existing, simple, series-produced pumps for the purpose. There have been some studies on a concept known as PAT (Pumps As Turbines), see [8] and [5]. It turns out that small pumps can be run inverted, as turbines, with a reasonably high efficiency. Typical applications for such turbines so far have been in small hydroelectric power stations to serve individual buildings near a river or a stream that are not connected to a reliable public power grid.

One of the reasons that make the PAT concept attractive is that small pumps can be purchased ready-made almost anywhere in the world. If there is a desire to increase the pump efficiency, it can be achieved by rounding off the pump blades’ edges at the outlet (which becomes the inlet when operated as turbine).

As a general term, very small turbines, with a power below 5 kW, are known as piko turbines. Examples of such can be found in, for example, Indonesia [6] and Kenya [7].

3.2. Prototype and test rig

In cooperation with a pump manufacturer, a prototype of a turbine-driven pump has been constructed. The prototype is of a purely mechanical type, with a common shaft, and is shown in Figure 1. The turbine pump was built by the pump manufacturer and tested in their laboratory. After that, it was installed in a DH substation in Gothenburg. The purpose of the field test was to see how the device fits in a DH substation environment, regarding both size and performance.

A larger building owned by Göteborgs Energi AB (GE), which serves as their head office, was chosen for this purpose, depending on confidentiality requirements that would be difficult to achieve if the prototype was put in a building with outside owners. The choice of the building has influenced the design and outcome of the experiment to some extent, which will be discussed later on.

The existing substation consists of a radiator circuit, a ventilation circuit and a domestic hot water circuit. Figure 2 shows the circuits’ respective HEXs and associated control valves.

Since the building is relatively large, its radiator circuit is divided into four sections, each with its own associated valve group and circulation pump (furthest to the right in Figure 2). The existing valve group configuration is shown in Figure 3.

The original idea was to connect the prototype in series with the radiator HEX and control valve. However, this turned out to be impossible because the differential pressure in GE’s network was found to be surprisingly low in the central part of the town where the building is located, typically 1-3 bars. With a series connection, the available differential pressure across the turbine would be far too low, since the pressure drop across the HEX and control valve would reduce it. Furthermore, because of the use of valve groups, the flow resistance on the secondary side could vary during the tests.
Therefore, we decided to use only one of the valve groups as secondary circuit and to connect the turbine directly to the DH pipes, see Figure 4. The prototype was connected so that the pump part replaced the existing circulation pump. The connection was made using flexible hoses. Two flowmeters were installed to measure the primary and secondary flow through the turbine pump.

The valve group that serves the basement was chosen for the tests, in order to minimise any effect on the operation of the building. The flexible hoses and the valve group’s appearance without protective cover can be seen in Figure 5. We could control the flow resistance on the primary and secondary side by means of shut-off valves. A test run showed that the flow resistance on the secondary side was too large relative to the turbine pump’s capacity. Therefore, an additional bypass between the pump inlet and outlet was arranged (not in picture). In this way, more relevant operating conditions could be tested. The tests were run at five different flow resistances.

The tests began by choosing a flow resistance on the secondary side. Then a shut-off valve on the primary side was opened gradually until a desired pump speed was achieved. When the state was stable, differential pressure and flow rate on primary and secondary sides were registered. The differential pressure was read directly from the installed pressure gauges and the flow was measured with an ultrasonic flowmeter from Kamstrup.

A difficulty was, as already mentioned, that the differential pressure in the DH network was quite low while we did our tests, and tends to be low in that part of the network throughout the year. For this reason, secondary flows of a certain magnitude could not be achieved because the pump speed could not be increased although the shut-off valve on the primary side was completely open. Another difficulty was that the differential pressure varies a lot in the DH network from time to time. Therefore, it was difficult to achieve completely steady states (constant pump speed). This has affected the measurement accuracy more than the fact that relatively simple equipment was used for pressure measurement.
4. RESULTS

4.1. Pump curves

Figure 6 shows the pump and system curves that were compiled from the experiments in Gothenburg. Different primary flows result in different pump speeds. The different system curves have been achieved by changing the radiator system characteristics using both a balancing valve to increase the system’s flow resistance, as well as with the bypass connection that reduces the relatively high flow resistance by allowing a part of the flow to bypass the radiator circuit. The steepest curve corresponds to a case where the resistance was increased (System 1), while the second-steepest system curve represents the original system (System 2). The remaining curves are variants in which the resistance has been reduced by a gradual opening of the bypass connection. In the regular system (System 2), the radiator flow at normal operation was between 0.61 and 0.625 l/s. The figure shows that this flow was not quite reached during the test. At the maximum primary flow through the turbine pump, a radiator flow of 0.56 l/s was reached.

4.2. Securing heat supplies

The pump curves show that the turbine pump as such works in the tested environment. The question is whether it provides enough flow at different operating conditions. Let us, to begin with, study the possibilities of using the turbine pump as backup device in case of a power failure.

During the test, about 90 percent of the normal radiator flow was reached. Since the radiator flow and radiator system characteristics normally are more or less constant, the flow is determined by the current differential pressure and flow on the primary side. The primary differential pressure varies with the outdoor temperature and depends on the DH network and the DH production characteristics. At the lowest outdoor temperature, the differential pressure has its maximum, which is favourable in terms of achieving a sufficiently high speed of the turbine pump. It can therefore be recognised that, with the current configuration, one clearly has an adequate backup solution at hand.

The magnitude of the maximum available primary flow is not entirely obvious. In the present installation, the turbine pump is connected in parallel with the radiator HEX allowing a high flow through the turbine. In a further perspective, in which turbine pumps are present at several locations in a DH network, this configuration allows the turbine to “steal” flow from other DH substations in the network. This means that one has to add more pump energy to the network. By installing the turbine in series with the radiator HEX, one can avoid this by allowing the turbine pump to receive the flow determined by the radiator system’s heat load.

The radiator circuit in question is designed for 56 kW and a temperature programme of 80/60°C. This means that the radiator flow is 0.67 l/s, which is roughly in line with what was noted during the tests. Since the primary side is designed for 100/63°C, the maximum primary flow rate is 0.36 l/s.

Figure 7 shows the radiator flow as a function of the DH flow for each test. Regardless of the flow resistance in the radiator system, a DH flow rate of approximately 0.4 l/s is required to achieve a flow on the secondary side to arise.

\[ \dot{Q}_{\text{rad}} = \rho \cdot \dot{V} \cdot c_p \cdot \Delta T \Rightarrow \dot{V} = \frac{56}{4.18 \cdot (80 - 60)} = 0.67 \text{ l/s} \]
Should the prototype of the turbine pump be placed in series with the radiator HEX it can be concluded that the required heating flow for the radiator HEX is not enough even to get the pump to begin to rotate (0.36 < 0.4 l/s). Discussions with the pump manufacturer indicate that it is possible to significantly reduce the friction by the right selection of components and technical solutions. Furthermore, the prototype is substantially oversized: the pump can, at full speed, provide a flow of 5.6 l/s at 50 kPa pressure drop on the secondary side. In a smaller pump, the effect of friction would be less under the given conditions. It is therefore relevant to analyse the turbine pump’s performance under the assumption that the friction can be significantly reduced. In such a case, the curves in Figure 7 are moved to the left so that the lines would coincide close to the origin.

4.3. Continuous operation of a turbine pump

Over the years, pump manufacturers have made efforts to improve the efficiency of their products to help save electricity. The idea of having a pump driven by a turbine would be a major, indirect step forward in this sense because the device uses energy that otherwise would not be utilised.

Figure 8 below shows a simplified schematic view of the pressure change from a pump located centrally in the network to the network’s periphery. The pressure difference between the supply and return pipe is much larger near the pump compared to the periphery of the network.

With reference to the previous section, there is a potential to use the turbine pump for continuous operation. Besides the offset error due to friction in the turbine pump, the attained secondary flow was significantly lower than the primary flow. A turbine pump for continuous operation requires a very careful design. Depending on the characteristics of different radiator systems the conditions vary how well a turbine pump can operate. Figure 9 below shows how the relationship between primary and secondary flow usually differs between different types of radiator systems. Best conditions are achieved in a low-flow system, 80/35°C in the figure, where the radiator flow is considerably lower than in a 60/40°C system. The highest secondary flow is found in a 55/45°C system, which is most demanding for the turbine pump.

In addition to a careful design, it may be necessary to use a different gear to obtain the correct relationship between the primary and secondary flows. As the flow ratio also varies with the heat load, it may be difficult to use a turbine pump with direct connection. In this case, an indirect link with generator and motor could be interesting.

5. RESULTS FROM THE PUMP MANUFACTURER

As mentioned before, the prototype was tested by the pump manufacturer before it was installed in Gothenburg. The results of these tests correspond with our results, but are far more comprehensive because the manufacturer used a laboratory and thus had no difficulty in achieving the desired differential pressure across the turbine section. The picture to the left in Figure 10 shows the results on the turbine side, while the picture on the right shows the results on the pump side. Curves with the same colour correspond to the same, roughly constant, shaft speed that was reached at the respective test series. One can see that at a constant primary flow and shaft speed, the pressure drop across the turbine varies rather little regardless of the load variation on the pump side. One can say that the turbine’s throttling ability depends mainly on the primary flow and that the pressure drop increases with the square of the flow, as in a component with a fixed flow resistance. The pump curves to the right are typical for a centrifugal pump.

Because of an appropriate choice of turbine and pump, the turbine is here working at a much higher pressure difference than the pressure head generated by the pump, but its flow need is only a third of the pump flow. This represents a typical situation in a substation. We can again try to determine if the turbine pump is suitable for continuous operation.
In Figure 11, the same pump curves as in Figure 10 are plotted as a function of the ratio between the obtained secondary flow (pump flow) and the required primary flow (turbine flow). Here we see the potential: up to 2.5 times depending on the necessary pump pressure head.

If this is compared with the curves in Figure 9, it appears, however, that such a flow ratio is not sufficient to run a radiator circuit dimensioned according to a 60/40°C temperature programme, except for very low outdoor temperatures. However, the situation is much better in the case of a low-flow system, 80/30°C. Here, the flow ratio is sufficient for outdoor temperatures up to around 5°C. One must be aware that to achieve a constant circulation flow the turbine pump must maintain a constant shaft speed, which requires a constant primary flow, which in turn goes against the principle of the control of the radiator HEX (variable primary flow) when the turbine pump should be connected in series with the latter. To solve this problem, the turbine pump needs to be designed to provide the adequate circulation flow at a given outdoor temperature and a bypass valve needs to be installed, allowing a bypass flow that is superfluous for the pump drive, but is necessary for heat supply at all lower temperatures.

Generally, it is clear from Figure 9 that a turbine pump with the discussed design can never run the radiator circuit throughout the entire operating range as the primary flow becomes very small at low loads. Some kind of assistance will therefore always be needed at moderate outdoor temperatures. However, there are prospects for how the limit for turbine pump-based operation can be moved towards higher outdoor temperatures:

- The constructed prototype is not fully developed and consists of two standard pumps with a mechanical coupling between them.
- The pressure rise in the radiator circuit was set to a typical value in our example. In a high-flow system adjusted as a low-flow system, this value would be considerably lower.
- The discussion this far requires a radiator system with constant circulation flow. In a system with a variable flow, the flow would decline with decreasing heat load, which would increase the turbine pump’s possible operating range further.

Even under the conditions mentioned above, the operation of the turbine pump would cover the majority of the radiator circuit’s operational time during the year, which means savings of electrical energy for the pump operation.
6. CONCLUSIONS

If the ambition is to supply heat to all buildings in the event of a power failure, the pressure variations across the network needs special attention. In places where there is a large pressure difference, the conditions for achieving a high efficiency in a turbine-driven pump are better than elsewhere. If the turbine pumps in DH substations located far from the circulation pumps should be able to work during a power failure, it is important that the control of DH substations operating at a high differential pressure does not allow an excessively large primary flow and thus steal flow so that the differential pressure will be less far from the pump.

The study supports the idea of making DH able to provide the connected buildings with heat in the event of a power failure. This may be done through natural circulation, a turbine-driven pump or a combination of both. If it also is possible to let the pump run continuously driven by the turbine, savings of electricity can also be achieved.

7. DISCUSSION AND FURTHER STUDIES

While it is clear that the turbine pump can serve as a backup system in a DH connected radiator system (if the operation of the DH network is maintained) more studies are required to explore the possibilities of continuous operation. Varying flow conditions between primary and secondary side at different load cases, for example, states that one should consider a hydraulic bypass of the turbine, which could be complemented by an electrical connection between primary and secondary side via a generator and an electric motor, preferably with a power grid-connection, see Figure 12. In a simple design, a combined generator/motor could be mounted on a common shaft between the turbine and pump, as in Figure 12.

![Figure 12. Possible connection of a turbine pump with integrated electric control.](image)

Another possibility is to allow the turbine to drive a generator that would supply the pump motor with electricity. In the latter case, the pump and turbine would have different speeds. However, it must be kept in mind that both the generator and the engine have a certain efficiency, which affects the overall efficiency of the device. Figure 13 shows how the efficiency is affected when changing from purely mechanical coupling (left) to full hybrid coupling (right). Note that the picture is simplified and that for the sake of simplicity it is assumed that each of the components have an efficiency of 50% which need not be the case in reality. Continued studies of hybrid systems should be preceded by an analysis of the components’ performance.
Figure 13. The impact of the number of components and the components’ efficiencies on the overall efficiency.

The results have been presented to Göteborg Energi’s Foundation for research and development at a seminar. In the discussion, it was emerged that even if the turbine pump device is not fully developed yet, the concept gives goodwill for the industry. The product could be particularly interesting for smaller customers that have difficulties to establish backup power but have a strong need to maintain thermal comfort, such as elder care, etc.

The important prerequisite for the concept is that DH utility has backup power in order to maintain production and distribution of heat. This is important also in view of the risk of freezing of pipes during cold weather.

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REFERENCES


RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.
IMPROVED COOLING OF DISTRICT HEATING WATER IN SUBSTATIONS BY USING ALTERNATIVE CONNECTION SCHEMES

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Abstract. In order to gain thermal efficiency in a district heating (DH) system, it is important that the return temperature from the connected buildings be kept as low as possible. When using indirect DH connection, the choice of connection scheme in the substation affects the DH return temperature. For example, in multi-dwelling buildings, the so-called 2-stage connection scheme is most commonly used. Traditionally, the 2-stage connection scheme is claimed to increase the cooling of DH water. However, the gain when used with modern space heating systems is moderate or non-existent, due to a shift from higher to lower temperature levels in the heating system, e.g., from 80/60°C to 55/40°C or even lower. To improve cooling of DH water, an alternative type of connection scheme, termed series connection, is suggested for buildings with domestic hot water (DHW) circulation. The gain from this connection is even larger for non-residential buildings where the DHW consumption is smaller.

In the series connection scheme, the heat exchanger (HEX) for DHW provision is placed before the HEX for the space heating system. The DH return temperature from the DHW HEX is, for most of the year or, in some cases, always, higher than the temperature level in the space heating system, when no DHW is tapped off and only re-circulation of DHW prevails.

In order to verify the gain in cooling of DH water, simulations have been performed using well-tested computer models of substations, including both space heating load and DHW consumption patterns. The magnitude of the gain from the series connection scheme is dependent on, among other things, the size of the building. In a building with a conventional radiator system, the gain from the series connection scheme in some cases estimates to several degrees C on the yearly average return temperature. The lower the temperature levels in the space heating system, the larger the gain from the series connection. This is a fact that agrees with the increased popularity of low-temperature heating systems, such as floor heating.

Keywords: district heating, low return temperature, substation connection schemes

1. INTRODUCTION

For many years, return temperatures in district heating (DH) networks have been an important issue for DH research. Many types of production units, as well as DH networks, benefit from low system temperatures. In Sweden, DH is the most common heating source for multi-dwelling and non-residential buildings, with a market share of more than 80%. The buildings in Sweden are, as well as in many other countries, connected via a so-called indirect connection to the DH network, i.e., the DH network (primary side) and the house-internal systems (secondary side) are hydraulically separated by heat exchangers (HEX). This study will focus on indirect connection.

Space heating and provision of domestic hot water (DHW) is characterised by a variation of temperature levels which provides a basis for lowered primary return temperature (increased cooling of primary water), by employing cascading of HEXs in substations.

With modern low-temperature heating systems, state-of-the-art substations with either parallel (also referred to as 1-stage) or 2-stage connection schemes are not always designed in a way that is optimal for the cooling of primary water, i.e., achieving the lowest possible primary return temperature for a given primary supply temperature. In this paper, two alternative connection schemes are investigated. Traditionally, radiator systems in Sweden have been designed for a temperature programme of typically 80/60°C (secondary supply/return) or 60/40°C at design outdoor temperature (DOT). However, previous work show that oversizing of heating systems is common, which means that a compensation, of either a reduced supply temperature or a reduced mass flow (so-called low-flow system), must be applied in order to achieve the desired indoor temperature.

Well-insulated windows, among other things, have led the way for building-integrated heating systems such as underfloor heating, working at substantially lower temperature levels. Underfloor heating has gained large popularity in detached houses, but is likely to become more common also in multi-dwelling buildings, not only in new buildings but also in older buildings, e.g., when renovating bathrooms. Today, bathrooms are instead often equipped with electric underfloor heating.
1.1. Objective

The objective with this study is to find out whether the state-of-the-art connection schemes are optimal for lower secondary temperatures, with respect to achieving the lowest possible primary return temperature. They will be compared with two alternative connection schemes.

1.2. Limitations

Instantaneous water heaters are assumed, since this type of heaters are quite common, especially in bigger installations, where load aggregation inside the building reduces peak values of hot water loads (the reason why the hot water system does not have to be dimensioned for a peak flow as high as would be the case if adding the expected peak flow in all units in the system). Indirect DH connection has already been mentioned, i.e., HEXs provide hydraulic separation between DH network and building-internal systems. When simulating DH substations with cascading, the area relation between pre- and after-heater (PH and AH, respectively) in the DHW HEX is set to 60 and 40%, respectively.

2. DESIGN OF DH SUBSTATIONS

Figure 1 below shows two common connection schemes for DH substations: parallel (or 1-stage) and 2-stage connection. In the figure, simulated median temperatures for a three-day period are indicated for an outdoor temperature of $8^\circ C$ (the average annual temperature in Malmö, Sweden) and a radiator system designed for a $60/40^\circ C$ temperature programme. The space heating and DHW systems are designed for 60 flats. The HEX for space heating is designed for a temperature difference of 3°C in the cold end of the HEX and the DWH HEX for 12°C, respectively, according to general guidelines [1], [13].

![Diagram of 2-stage and Parallel connection](image)

Figure 1. 2-stage (left) and parallel (right) connected DH substations with median temperatures level at $T_{out} = 8^\circ C$ and 60/40°C radiator design temperature (60 flats).

In some parts of Sweden, a 3-stage connection scheme is still rather common, although it is generally not installed today. At low outdoor temperatures, the DHW becomes overheated in the AH. A subsequent shunt valve reduces the temperature, but if the town’s water is too hard, there is a large risk of scaling of the DHW HEX.

A variant of the 3-stage connection scheme, termed Russian 3-stage connection was proposed by our research group in [10] and [7]. The primary temperature after the AH is typically around 50°C when no DHW is being tapped off and around 35°C when DHW is being tapped off. Given that the supply temperature to the heating system, at least for low-temperature systems, mostly is below this temperature level, it could be wise to connect the radiator HEX in series, after the AH, see Figure 2. The re-circulated DHW temperature should not be less than 50°C, due to the risk of legionella growth, which means that the primary water leaving the AH or DHW HEX is always hotter than 50°C when no DHW is being tapped off.

The matter of various connection schemes in DH substations has been dealt with by different publications over the years. Frederiksen & Wollerstrand [2] showed that, when instantaneous water heating was assumed, the gain in return temperature with 2-stage connection is rather small compared with parallel connection on a yearly average. Gummérus [4] by simulations supported this finding, which in turn was supported by derivation of analytical formulae for return temperatures and by laboratory experiments by Frederiksen et al. [3]. Results derived by Volla et al. [14] were
somewhat more encouraging for cascading in configurations when fan coil heating was added to a hydronic radiator system. Later findings by Snoek et al. ([10] & [11]) for similar configurations yielded smaller gains, the difference in the results from the two investigations largely to be explained by differing practices in induced hot air temperature level.

In [10], Frederiksen on theoretical grounds advocated that the simple parallel connection scheme is rather inferior to a parallel connection where re-circulated DHW is entered after a PH. In [6], simulations provided numerical support for this view. Intuitively, and from an exergetic point of view, it is in fact rather obvious that mixing incoming, cold town’s water with much warmer re-circulated hot water represents a substantial thermodynamic loss. Nevertheless, the simple parallel connection scheme is generally shown by the Swedish District Heating Association [13]. Therefore, in practice, it is quite commonly used.

2.1. Alternative connection schemes

A further proposition was made by Frederiksen in the work [10], supported by analytical and graphical derivations: When a substantial amount of re-circulated hot water is supposed, in combination with a low-temperature space heating system, there is a good thermodynamic case for adopting 3-stage connection instead of 2-stage. A modified variant of the 3-stage connection arrangement was recommended as a general solution, rather than the traditional Swedish type, since the alternative arrangement does not suffer from the previously mentioned drawback of sensitivity to hard town’s water, i.e., the scaling problem. This connection resembles a scheme found in Russian district heating literature, e.g., in the textbook [12] by Sokolov.

In this paper, this 3-stage connection scheme will from now on be denoted R3-stage, where the ‘R’ in the designation stands for ‘Russian’. It will be compared with another alternative connection scheme, along with the conventional parallel and 2-stage connection schemes, with respect to providing the lowest primary return temperature. The R3-stage connection scheme is shown in Figure 2 below. The other alternative connection scheme has been termed “series connection” and is shown in Figure 3. In both connection schemes, primary water used for DHW re-circulation is directed into the radiator HEX during part of the time.

![Diagram of R3-stage connected DH substations.]

Figure 2. R3-stage connected DH substations.

The idea with the R3-stage connection scheme is to cool the primary water as efficiently as possible by taking different paths through the substation. We explain by looking at control strategies at different operating cases:

Let us follow the incoming primary flow \((\dot{m}_p)\) through valve R0 to the AH HEX. R0 operates independently of the space heat load and keeps the DHW temperature at the desired level by controlling \(\dot{m}_p\) through the AH. After leaving the AH, the flow continues through the RAD HEX, during the heating season. If the desired heating system supply temperature level is not reached, valve R1 opens and allows more primary flow to mix with the flow leaving the AH. In order to avoid overheating of the space heating system, R2 opens and allows a bypass flow from the AH directly to the PH when
valve R1 is closed. Note that all primary flow passes through the PH. Below, the control strategy is explained in a different way:

- \( T_{ss} < T_{ss, setpoint} \) & \( R2 = 0 \) (bypass closed) \( \rightarrow \) R1 opens (increased \( \dot{m}_p \) to RAD HEX through R1)
- \( T_{ss} < T_{ss, setpoint} \) & \( R2 \neq 0 \) (bypass open) \( \rightarrow \) R2 closes (decreased bypass flow from AH through R2)
- \( T_{ss} > T_{ss, setpoint} \) & \( R1 \neq 0 \) (\( \dot{m}_p \) to RAD HEX through R1) \( \rightarrow \) R1 closes (decreased \( \dot{m}_p \) to RAD HEX through R1)
- \( T_{ss} > T_{ss, setpoint} \) & \( R1 = 0 \) (no flow through R1) \( \rightarrow \) R2 opens (increased bypass flow from AH through R2)

The idea with the series connection is the same as with the R3-stage connection, i.e., to utilise the rather high primary water temperature after the DHW HEX when no DHW is being tapped off. Both the R3-stage and the series connection schemes require more sophisticated control equipment than the conventional connection schemes. However, the latter connection scheme is a simplified version of the previous one. In contrast to the R3-stage connection, the series connection only alters between two operating modes, depending on whether DHW is tapped off or not.

The primary water supplying the DHW HEX is always led into the radiator HEX when no DHW is tapped off. When necessary, e.g., during high heat load when the primary flow from the DHW HEX is insufficient, additional primary flow is mixed by a bypass connection supplying the HEX with more primary water. When DHW is tapped off, the valve R2 will open, and the substation will work as a regular parallel-connected substation and the radiator HEX is supplied with primary water through the bypass connection.

As already mentioned, the parallel connection scheme can be designed in two different ways: generally there is only one DHW HEX, as shown in Figure 1, but the DHW HEX can be divided into two parts, referred to as PH and AH. The influence of this difference will also be studied, both for the parallel and for the series connection schemes. One can say that the reason for showing two heat exchanger design cases for the parallel connection scheme is that it is a matter of taste to say which design case provides the fairest basis for comparison between the various connection schemes.

3. MODELLING THE DH SUBSTATION AND HEATING SYSTEM

The mathematical description of the substation and heating system model is based on well-documented models of HEX, control equipment, actuators and valves. The theory and function of these components have been described in detail by a number of authors, for example [4], [5], [8] and [9]. The components are combined into a model of a DH substation in the software Simulink.

3.1. Prerequisites

Patterns for DHW use (tap frequency and tap length) are simulated based on statistical measured data for different number of residential flats. The patterns are simulated with a program described in [15]. The heat load is assumed to be 3 kW per flat at design outdoor temperature, \( T_{DOT} \), (set to \(-15^\circ C\)) and zero at \( T_{out} = 17^\circ C \). The design DHW load is
based on recommendations from the Swedish DH Association [13]. The temperature levels in the DH network are based on the design temperatures given in [13]. Heat losses from the DHW circulation circuit to the building is based on a temperature drop of 5°C and an energy loss of 0.1 kW per flat. These assumptions are shown in Figure 4. The diagram on the left also includes the duration of the outdoor temperature in Malmö.

![Diagram](image1.png)

Figure 4. DH supply temperature and relative space heat load as a function of the outdoor temperature along with the outdoor temperature duration on the left and design heat load for space heating and DHW as a function of the number of flats on the right.

The primary return temperature is simulated for four different radiator system temperatures: 60/40, 75/35, 55/45 and 40/30°C, respectively. The 40/30°C programme is a low-temperature radiator programme that can be assumed typical for modern buildings. For residential buildings, five different sizes are simulated: 15, 30, 60, 90 and 120 flats, respectively. The different temperature programmes for the heating systems are shown in Figure 5.

![Diagram](image2.png)

Figure 5. Different temperature programmes for the heating system. Blue lines show corresponding return temperatures.

Primary flow-weighted average return temperatures for one year are simulated for the different combinations of DH substation schemes and radiator temperature programmes, see equation (1). The temperature is weighted with the primary flow rate.

\[ T_{pr} = \frac{\sum T_{pe} \cdot \dot{m}_p}{\sum \dot{m}_p} \]  

(1)

4. RESULTS

4.1. Residential buildings

Figure 6 shows the yearly average primary return temperature for a residential building. Each diagram shows results for different connection schemes for a specific radiator temperature programme as a function of the number of flats. As
seen in the figure, the simple parallel connection is inferior to the other connection schemes for all temperature programmes. However, a parallel connection scheme with DHW provision divided into PH and AH can, for heating systems designed for 60/40, 40/30 and 75/35°C, compete with the 2-stage connection. The R3-stage connection scheme gives the lowest return temperature under all conditions. In newer buildings with low-temperature space heating, the R3-stage connection could increase the cooling of primary water with 1.5-3°C (compared with a 2-stage connection) depending on the size of the building. 2-stage connection is often chosen instead of the cheaper parallel connection in order to reduce $T_{pr}$. Our study shows that this only makes sense when comparing with the simple parallel connection without DHW provision divided into PH and AH. Regarding the series connection, the following can be observed: it gives approximately the same return temperature as the 2-stage connection and the parallel connection with PH/AH, except for the 55/45 programme (and to some extent 60/40) were the 2-stage connection is slightly better. However, the series connection with PH/AH is the second best choice after the R3-stage connection under almost all conditions.

Figure 6. $T_{pr}$ for residential buildings. Each diagram shows results for different connection schemes for a specific radiator temperature programme.

Table 1 shows the results from Figure 6 in a different way. The 2-stage connection scheme is used as reference and in the column for the other connection schemes are indicated whether they give a lower, higher or equal primary return temperature.
Table 1. Results from simulations. A reduction of $T_{pr}$ > 1°C is indicated by ‘−’, a reduction between 0.3-1°C by ‘(−)’. An increase in $T_{pr}$ of > 1°C is indicated by ‘+’, an increase between 0.3-1°C by ‘(+). Changes less than ± 0.3°C are indicated by ‘/g97’.

<table>
<thead>
<tr>
<th>Temperature program</th>
<th>2-stage</th>
<th>R3-stage</th>
<th>Parallel</th>
<th>Series</th>
<th>Parallel with PH/AH</th>
<th>Series with PH/AH</th>
</tr>
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<td>8060</td>
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<td>−</td>
<td>+</td>
<td>(+)</td>
<td>(+)</td>
<td>~</td>
</tr>
<tr>
<td>5545</td>
<td>30.1</td>
<td>−</td>
<td>+</td>
<td>~</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>6040</td>
<td>29.0</td>
<td>−</td>
<td>+</td>
<td>(−)</td>
<td>−</td>
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<tr>
<td>7535</td>
<td>28.0</td>
<td>−</td>
<td>+</td>
<td>(−)</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>4030</td>
<td>26.8</td>
<td>−</td>
<td>+</td>
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<td>(−)</td>
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<td>5545</td>
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<td>4030</td>
<td>22.7</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>~</td>
<td>(−)</td>
</tr>
</tbody>
</table>

4.2. Non-residential buildings

Many DH connected buildings are used for non-residential purposes. The use of DHW generally differs quite a lot compared to residential buildings, depending on the type of activities. For example, in an office building, there is little DHW consumption during evenings, nights and weekends and the consumption during working-hours is generally smaller than in a residential building of the same size (less showering, cooking etc.) Therefore, simulations with a reduction in the number of DHW tappings with 25 and 50%, respectively, were performed. The size of the tap flow is not changed, which means that the DHW HEX is designed for the same flow rate as for a residential building with the same space heat load, as are the heat losses for DHW circulation. Simulations were made for buildings dimensioned for 180, 270 and 360 kW heat load, respectively (corresponding to 60, 90 and 120 flats, respectively). Simulated radiator temperature programmes are 60/40, 55/45 and 40/30°C, see Figure 7.
As seen in the figure, the 2-stage and the parallel connection schemes give about the same primary return temperatures, regardless of whether DHW provision is divided into PH and AH or not. However, the series connection (both with and without division into PH/AH) and the R3-stage connection gives drastically reduced return temperatures; the difference is in the order of 3-4°C depending on the radiator system temperature.

With a reduction of the number of tappings with 50%, the gain with the series connection and the R3-stage connection is even better; 4-6°C, see Figure 8.
Temperature program: 6040 tap reduction 50%

Temperature program: 5545 tap reduction 50%

Temperature program: 4030 tap reduction 50%

Figure 8. Three different temperature programmes with reduction of the number of tappings with 50%.

7. DISCUSSION AND FURTHER STUDIES

DH substations that increases the cooling of primary water is favourable to the DH utility and in many cases also to the DH customer if the DH price is based on both energy consumption and cooling of primary water.

At all load conditions, the simple parallel connection scheme is the poorest, i.e., gives the highest return temperature. The R3-stage connection scheme always gives the lowest primary return temperature. However, this connection scheme needs a more sophisticated control. The commonly used 2-stage connection scheme is not always the best choice with respect to lowest possible return temperature. In some cases, a parallel connection scheme using the same HEX layout as the 2-stage connection, i.e., with PH and AH and the DHW re-circulation connected in between, gives approximately the same return temperature. The series connection gives a lower the return temperature compared to parallel connection and lower than the 2-stage connection in smaller residential buildings. With division of DHW into PH and AH, the series connection gives a lower return temperature than the 2-stage connection.

In buildings with less DHW consumption, e.g., non-residential buildings, the series connection and the R3-stage connection gives primary return temperatures in the same order, several degrees lower than the traditionally used connection schemes. In these cases the influence of dividing the DHW reparation into PH and AH is negligible.

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REFERENCES


RESPONSIBILITY NOTICE

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District heating in case of power failure

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ABSTRACT

Power failures in combination with harsh weather conditions during recent years have led to an increased focus on a safe energy supply to our society. Many vital functions are dependent on electricity; e.g., lighting, telephony, medical equipment, lifts, alarm systems, payment, pumps for town’s water and, perhaps the most critical of all, heating systems. In Sweden, district heating (DH) is the most common type of heating for buildings in town centres. Therefore, it is of great interest to investigate what happens in DH systems during a power failure. The present study shows that, by maintaining the DH production as well as the operation of the DH network, possibilities to supply connected buildings with space heat are surprisingly good. This is due to the fact that natural circulation will most often take place in radiator systems. In Sweden, and in many other countries, so-called indirect connection (heat supply across heat exchangers) of DH substations is applied. If a DH network operation can be maintained during a power failure, DH water will continue to pass the radiator system’s heat exchanger (HEX), provided that the control valve does not close. The radiator circulation pump will stop, causing the radiator water to attain a relatively high temperature in the HEX, which promotes a natural circulation in the hydronic heating system, due to an increased water density differential at different temperatures. Several field tests and computer simulations have been performed and have displayed that almost all buildings can achieve a space heat supply corresponding to 40–80% of the amount prior to the interruption. A sufficient heat load in the DH network can be vital in certain cases: e.g., for ‘island-operation’ of an electric power plant to be performed during a power failure. Furthermore, for many combined heat and power stations, a requirement involves that the DH network continues to provide a heat sink when no other cooling is available. Based on the findings presented herein, a set of recommendations have been set up to provide advice to, among others, DH utilities and owners of customer buildings.

1. Introduction

A large-scale power failure affects numerous vital functions of society, among them space heating. Obviously, during a power failure, heating systems that depend on electricity being converted into heat energy (either directly or via a heat pump) cannot operate at all, and boilers (oil, natural gas, pellets, etc.) are also prevented from functioning, since electricity is required for the operation of burners and control equipment.

District heating (DH) is common in many countries and in, e.g., Denmark, Finland and Sweden it constitutes the dominating method for heating larger buildings. Thus, 76% of the total building floor area of multi-dwelling houses in Sweden is heated with DH [17], and it is for this reason of vital interest to study what can be expected to happen in such buildings in case of a power failure, assuming that the production of DH can be maintained. Hydronic radiator systems in modern buildings are fitted with circulation pumps whose motors stop when the electricity supply fails. Consequently, the heating of buildings connected to a DH network is generally assumed to stop functioning in such an event. Nevertheless, as will be demonstrated in this paper, a substantial natural circulation effect caused by an increased water density differential takes place in many cases.

The major power failures that have occurred in recent years have led to an increased focus on the possibility of a local production and distribution of electric power during a breakdown of the national power grid, so-called ‘island-operation’. In order for the production of electricity in combined heat and power (CHP) stations to be maintained, it is necessary that excess heat continues to be removed from the power generating plant. If it is possible to use the DH network as a heat sink, i.e., if buildings connected to the DH network carry on consuming heat energy, provisions for additional cooling of the plant may not be necessary.

For our society, it is essential that building heat supplies be maintained, especially in the event of a power failure of long duration during harsh weather conditions. If evacuations of people from buildings can be avoided, or at least delayed, this will help protect especially elderly people and persons in need of health care from risky exposure to low air temperatures.

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1.1. Objective

The objective of the present study was to investigate what can be expected to happen in space heating systems connected to DH when a power failure occurs. It was explored whether it is possible, provided that the DH network water circulation and heat transportation continues to function, for natural circulation to arise in space heating systems, and if so, to what extent. Natural circulation has been used in the past, whereas modern systems are designed for pump circulation to overcome a significantly higher flow resistance in pipes of smaller diameters.

Several field studies have been carried out to investigate the potential for natural circulation in a variety of building types. Additionally, computer simulation has been employed to study variation effects of system parameters. Based on results from these investigations, we have set up recommendations for how the concerned parties can be appropriately prepared to minimise hazard risks. The results form a basis for municipal risk planning.

1.2. Securing heat supply

The presented project was carried out in co-operation with, among others, the municipality of Malmö (Sweden’s third largest town with 290,000 inhabitants). An analysis of the society’s vulnerability to a power failure of long duration during harsh weather conditions pointed out an interrupted heat supply as the most serious threat for the inhabitants as well as for municipal activities such as health and geriatric care [5]. Certain buildings and activities have back-up power, e.g., hospitals, the town house, as well as the water supply and sewage plants.

Shortcomings in the preparedness for elder care has been demonstrates [23] and it was found that more than 40% of the facilities in Sweden lacked access to back-up power or heat. Another study [2] presented similar results. Limits for acceptable duration of outages have been set to six hours for care facilities and to 24 h for dwellings [4].

One of the most well known power failures occurred when an ice storm hit Canada in 1998. 4.7 million people were left without power and heat for a prolonged period in the middle of winter, which demonstrated the need for planning and the benefit of emergency preparedness [9], [11]. There were no DH systems in the area; instead heating was primarily obtained from electricity and oil. The blackout caused extensive evacuations; many people could move in with relatives and friends while others had to stay in public shelters. Studies have shown that people felt that the most significant strain consisted in trying to keep warm [22].

The storm Gudrun that struck southern Sweden in January 2005 caused widespread, long-lasting blackouts and became a reminder of how vulnerable our society is when energy supplies fail. However, the weather was relatively mild and larger towns with DH systems did not have as long-lasting power failures as smaller towns without DH [20]. Nevertheless, the present investigation demonstrates that a small village that could restore the DH network regained approximately 80% of the heat load, despite the fact that most customers had no electricity. This indicates that natural circulation occurred for several customers.

DH is generally considered to be a reliable technique, cf. for instance a Finnish study [12], and in the USA, DH is often presented as a very reliable form of energy supply [24]. The starting point for this work, however, is to study the implications for DH if a power failure occurs.

1.3. Island-operation

In August 2003, 50 million people in the north-eastern USA were affected by a power failure, and certain areas were without power for four days. Although DH is relatively small in the US, small-scale co-generation is rather common. For example, a CHP unit can provide a university campus, hospital, industrial or residential building with both power and heat, and sometimes also cooling. One study [1] describes how different CHP systems acted in connection with the power failure. The vast majority, including units not designed for stand-alone operation, functioned satisfactorily during the blackout. The heat load was rather low during the time in question, but the ability to maintain, or restore, the power supply in these systems was of considerable importance to minimise the impact of the blackout.

An island grid should imply that all DH customers have access to electricity and thus to a functioning heat supply. In practice, however, island-operation signifies limited supplies of electricity that can be directed to particularly sensitive activities. The availability depends on which production facilities that can be employed and where they are located; many production units are situated in areas with low population densities.

If it is possible to employ the DH network as a heat sink, the use of additional cooling in the CHP unit may not be necessary. The DH supplier in Malmö, i.e., E.ON, was interested in determining whether, during a power failure, some of their CHP units could work in island-operation mode with the DH network as the only available heat sink. Even though there existed back-up power to operate the DH network during a power failure, there was no knowledge concerning what happens in customer installations, i.e., what level of heat supply, if any, can be expected.

It can be argued that the advance of the most centralised form of building heating represented by district heating, sometimes serving a majority of all buildings within a town, has made building heating more vulnerable in certain respects. On the other hand, as this paper attempts to demonstrate, DH possesses a great potential for upholding heat supply.

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**Table 1: Nomenclature**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
<th>Subscripts</th>
<th>Abbreviations</th>
</tr>
</thead>
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<tr>
<td>$g$</td>
<td>standard gravity (m/s²)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>height (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$l$</td>
<td>length (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>temperature (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho$</td>
<td>density (kg/m³)</td>
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</tbody>
</table>

| $p$         | primary return                       |            |                     |
| $r$         | return                               |            |                     |
| $s$         | secondary, supply                    |            |                     |

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<tr>
<th>Subscripts</th>
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<tr>
<td>$\infty$</td>
<td>infinity, steady state</td>
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<td>$i$</td>
<td>indoor</td>
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</tr>
<tr>
<td>$nat$</td>
<td>natural circulation</td>
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</table>

**Abbreviations**

- CHP: Combined Heat and Power
- DH: District Heating
- DOT: Design Outdoor Temperature
- HEX: Heat EXchanger
2. What happens with the heat supply when the power fails?

2.1. Production

This work focuses on what happens in the buildings connected to DH. If any heat is to be transferred, the DH network needs to function, at least to a certain extent. A Swedish study has demonstrated that conditions differ between places [19]. Some DH utilities have back-up power to keep the system in operation, while others do not, or are only able to protect their network from freezing. The issue is however important, not only because of the matter of natural circulation, but regarding whether customers with back-up power, such as hospitals, can expect to receive DH.

2.2. Substations

In many countries, a so-called indirect connection is adopted in DH substations, signifying that a heat exchanger (HEX) hydraulically separates the primary system (DH network) and the secondary system (house-internal), [16] and [3]. This paper is devoted solely to indirect DH connections. However, in some countries, direct connection is common. The use of HEXs is an obstacle for obtaining heat transfer between the DH network and the secondary systems when no electricity is available. When using direct connections, it should in general be easier to uphold the circulation in the secondary systems. A special type of direct connection has often been employed in Eastern European DH systems where ejector pumps are used in substations, rendering it possible to deliver heat, even if the customers are without electricity, [13] and [14].

The actuator manoeuvring the control valve in a substation is generally motor-driven and consequently depends on electric power in order to function. Generally, the control valve stops in its current position. Contacts with manufacturers show that closing valves are not used in heating systems since they are more expensive, whereas they are often used in domestic hot water systems to avoid the risk of scalding.

The circulation pump, powered by electricity, is another key component in the DH substation. The seemingly widespread perception that DH-connected systems stop functioning at a power failure is based on that the circulation ceases when the pump stops.

3. Natural circulation

3.1. Mechanism and history

Space heating systems built during the early days of central heating were constructed for natural circulation. When water is heated, its volume increases as a result of its density decreasing, and the water thus rises in the system. In reverse, when the water is cooled off in the radiators, the density increases and the water descends back to the heat source (see Fig. 1).

The pressure differential originating from natural circulation is proportional to the density difference and the height of the system according to the following equation:

\[ \Delta p_{\text{nat}} = (\rho_s - \rho_r) \cdot g \cdot h \]  

where \( \Delta p_{\text{nat}} \) is the differential pressure; \( \rho_s \) the water density in return pipe; \( \rho_r \) the water density in supply pipe; \( g \) standard gravity and \( h \) is the height difference between supply and return pipe.

More information regarding natural circulation can be found in reference [6]. By using large pipe dimensions in the distribution system and a boiler with a low flow resistance, pressure losses can be kept to a minimum and it becomes possible to achieve a sufficient circulation flow [15].

3.2. Natural circulation in pump-driven systems

Systems built for pump operation have significantly larger flow resistances due to smaller pipe diameters and the use of balancing valves. Modern plate HEXs also give rise to an increased flow resistance. Field studies have been carried out on 14 objects, including smaller and larger multi-dwelling buildings, single-dwelling and non-residential buildings. Although the results differed significantly, certain fundamental similarities existed between the tests.

When testing a building, the power supply to the radiator circulation pump was cut off and the control valve was set to manual mode, resulting in it becoming frozen in its current position. Temperature sensors were mounted on incoming and outgoing pipes to the HEX, both on the primary and secondary sides. The primary flow was obtained from the heat meter whereas the secondary flow was determined from a simple energy balance.

Fig. 2 describes the results of a field experiment with natural circulation. The upper diagram shows the temperature levels in the HEX, where the black lines indicate the primary side and grey lines represent the secondary side. The solid lines designate the supply and the dashed lines the return temperatures. The diagram in the middle shows the outdoor temperature and the lower diagram displays the secondary flow rate (black) and the heat supply (grey) relative to the level prior to the start of the test. Just before 9:45 AM, the power to the circulation pump was cut off and the control valve was frozen at the current position by placing it in manual mode, which caused the secondary flow to decrease drastically. Since the primary flow remained constant, the HEX became very hot and the supply temperature to the radiator system was increased – almost to the same level as the DH supply temperature. The heat supply was partly lost, and gradually recovered up to 90% of its initial level. Despite the flow being substantially decreased (to less than 15%), the increased temperature drop (from about 9 °C to 50 °C) recovered the heat supply in the radiator system. During the test, the radiator supply temperature displayed a gradual reduction when the natural circulation flow increased due to the primary supply temperature slightly decreasing.

![Fig. 1. A building with a hydronic radiator system connected to DH.](image-url)
In order to verify whether the relatively low natural circulation flow was evenly distributed in the system, supply and return temperatures on four (evenly distributed) risers in the basement were measured. The temperature front reached all four risers, indicating that the heat distribution in the system was indeed uniform, although the actual flow was not measured.

To summarise, it can be stated that natural circulation functioned very well in this object, giving rise to almost the same level of heat supply as during normal operation. The remaining objects showed more or less the same pattern (i.e., a small circulation flow rate but a significant temperature drop), although most of them did not reach the same level of heat output. Various obstacles for natural circulation could be identified, which is described in the next section. A more detailed analysis is presented in reference [8].

In total, five multi-dwelling, four single-dwelling and five non-residential (three schools and two retirement homes) buildings...
were investigated. Fig. 3 below shows the levels of heat supply which were reached in the tested buildings (in relation to the initial heat load). The tests were performed at outdoor temperatures between 0 °C and 9 °C.

### 3.3. Obstacles to natural circulation

The following section describes the most important obstacles to natural circulation in pump-driven radiator-heating systems that have been identified.

#### 3.3.1. The DH substation

Most types of control valves stop in their current position and are thus not a direct obstacle to natural circulation. Valves with spring-return are generally used for dampers in ventilation systems (to avoid freezing) and for domestic hot water systems (to avoid scalding), however not in radiator systems. Still, electromagnetic actuators are naturally closed if they lose power. Nevertheless, contacts with manufacturers demonstrate that these actuators are generally much less common than their electromechanical and electro hydraulic counterparts. The Swedish District Heating Association has now, as a result of this work, included in their recommendations that control valves for heating stop in their current position [18].

One type of DH substation was found which had primary and secondary supply pipes connected at the bottom of the HEX instead of at the top. Although the latter is the more common alternative, the connection of the supply pipes has no practical significance for the normal operation of the substation. However, it does affect the natural circulation. As demonstrated earlier, the secondary flow was reduced and became very hot. Without the pump in operation, the hot water in the HEX would rise and leave at the top, which would result in a reversed circulation flow. Under such circumstances, the HEX would work as a co-current flow HEX instead of one with a counter-current flow, as demonstrated in Fig. 4. In a co-current HEX, the outgoing secondary supply temperature is limited by the outgoing primary return temperature. The heat exchange is thus less effective due to the temperature loss. Contact with the manufacturer shows that this type of substation is rather uncommon.

#### 3.3.2. Heat distribution in the radiator system

The heat supply to buildings with reversed HEXs was found to be substantially reduced, but was still quite uniformly distributed. However, some of the other buildings received a more uneven distribution. Fig. 5 presents an overview of the heat distribution in two large objects, both built in the 1970’s, with six stories and with 143 and 196 flats. In both objects, two buildings were supplied by a joint substation via long distribution pipes running through a garage or underground. Furthermore, both objects had 1-pipe systems with relatively narrow pipe dimensions and, consequently, high pressure drops. The heat supply was estimated to approximately 50% of the original values for both objects. As seen in the figure, approximately half of the systems could receive heat, implying that this half worked satisfactorily whereas the other half did not work at all.

The question is which of the factors that represents the biggest obstacle – the 1-pipe systems, the narrow pipe dimensions or the horizontally extended systems.

Since old radiator systems had very large pipe dimensions, one could fear that the higher flow resistance in newer buildings could impair natural circulation. However, other objects show that this does not necessarily have to be the case. This is not surprising if one considers the physical link between pressure and flow. In hydraulic systems, the pressure drop can be assumed to be proportional to the square of the flow, provided that the flow is turbulent [25]. (One should note that, even during natural circulation, the flow can generally be proved to be turbulent.) In most of the tested

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objects, the natural circulation flow amounted to 10–15% of the normal flow rate. A tenth of the flow signifies that the pressure drop with natural circulation is only one hundredth of the normal pressure drop. Admittedly, the driving pressure for natural circulation was only 2–3% of the normal pressure, but this shows that narrow radiator systems need not be as restrictive to natural circulation as they appear at a first glance.

1-pipe radiator systems were common during the 1960–1970’s, due to an impatience to simplify and save pipe material. These systems are usually combined with narrow pipe dimensions and are found in large buildings. However, a 1-pipe system consisting of two circuits, one on the first floor and the other on the second floor, was also found in a single-dwelling house built in 1998. The substation was placed on the first floor, on a higher level than the bottom circuit and consequently no circulation occurred within it. On the second floor, the heat output was estimated to almost half of the total level before the test was started. However, almost all of the heat was emitted in the first two radiators (out of five). Risers that receive proper circulation in the larger 1-pipe systems seemed to function quite well, and since pressure drops become relatively small at low driving pressure, it thus seemed likely that the vertical and horizontal extension of the radiator systems was a more critical factor than age, pipe diameters, and the choice between 1- and 2-pipe systems.

A limitation for the experiments was that the tests could not continue more than a few hours in order not to jeopardise the comfort for residents or for activities in the buildings. In general, however, what can be described as stable conditions was achieved in the tested systems. Nevertheless, it is legitimate to consider what happens in systems where natural circulation is only established to a limited extent. Would it be possible for cold risers to receive natural circulation?

Important parameters include the ratio between the available driving pressure and the pressure drop in the horizontal distribution as well as the height of the risers and the pressure drop within them. Expressed in other words, the flow distribution is determined by the relationship between the height of the HEX, \( h_0 \), and height and the length of the system, \( h_1 \) and \( l \), respectively. These variables are indicated in Fig. 6. At first sight, it can be assumed that the natural circulation benefits from high risers, since the driving force is proportional to the height. However, this need not be the case.

As a result of the density difference of water, one can say that the system has a small virtual circulation pump at all points where there is a height, i.e., a riser (provided that there is a temperature difference between the supply and return pipe) and the DH substation. This is demonstrated in Fig. 6. Such an effect is always present in the system, even during operation of the pump, but is negligibly small as compared to the pump head.

Let us consider an extreme system that has a very large driving height at the HEX, situated in a low building with a small bottom area. This is a system with conditions similar to normal pump operation, with the main differential pressure arising from the substation. Conversely, we can imagine a system with a low driving height in the basement circuit while the risers are very high. The heat may then display difficulties reaching the entire system. The influence of the “pumps” in the functioning risers are much more significant than that of the “pump” in the HEX, which means that it is actually possible to obtain a negative flow in one or more risers beyond the last functioning riser. The higher the altitude difference in the substation, the higher is the driving pressure in the horizontal distribution (basement circuit) and the farther out the flow will reach. Following the same reasoning, a horizontally extended building has a negative impact on the flow distribution. Risers with a high pressure differential tend to “suck” flow from subsequent risers.

The negative flow is in itself no real problem, but it is important to be aware of the fact that, in certain buildings, natural circulation functions perfectly well in some parts of the building, while other parts receive no heat at all. This should be kept in mind for buildings that are very high and/or horizontally extended.

3.3.3. Ventilation

A natural ventilation system provides no direct means of controlling the ventilation. One associated drawback includes that it may often present a low circulation rate in summer whereas it is (too) high during winter. In case of a power failure during cold

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**Fig. 6.** A schematic drawing of pressure differentials in the system during natural circulation. The image indicates the height of the heat exchanger, \( h_0 \), the risers, \( h_1 \), and the horizontal extension of the system, \( l \), as well as the virtual pumps due to density differentials.

---

1 The density difference is approximately 10 kg/m³ at 65–45 °C, and assuming that the system is 10–20 m high, Eq. (1) gives a pressure difference of 1–2 kPa, which should be compared to a normal pump head of typically 30–100 kPa.
Weather, these buildings run the risk of cooling down faster. To a certain extent, one can say that this is offset by the fact that mainly older buildings have natural ventilation, and that such buildings have generally shown good results in terms of natural circulation in the radiator system.

Forced ventilation systems will allow very limited air flows without power, resulting in a reduction in the buildings’ heat losses. This is of course good, but also brings about an inferior air quality that, under the circumstances, is of less importance. Moreover, forced ventilation systems are generally equipped with dampers with spring-return to avoid freezing of air handling units.

Air handling units can be connected to the substation by, for instance, a separate ventilation circuit, supplying all air handling units, connected in parallel to the radiator circuit. This alternative does not give rise to any natural circulation since there is hardly any heat load or cooling of the water in this circuit. It is, however, quite common to connect both radiator and ventilation circuits to a joint circuit. The individual circuits are then connected to the main circuit using valve groups so that the desired temperatures and flows can be obtained. The most common type of valve group used with DH is shown in Fig. 7.

The main circuit is generally limited to the basement while the radiator and ventilation circuits reach the top of the building.

Therefore, the differential pressure in the latter circuit may be higher than the differential pressure in the former, but this naturally also depends on the temperature levels. It is then possible that the check valve in the valve group opens and allows part of the return flow to the supply pipe. In that case, the temperature to the secondary circuit becomes lower than the level in the main circuit. The results from a field test with a radiator circuit connected with a valve group are given in Fig. 8. It was likely that there occurred admixing of the return flow, which resulted in the reduced temperature. Nevertheless, the supply temperature sufficed for a certain amount of natural circulation to arise in this circuit.

3.5. General applicability

The field tests were conducted mainly in Malmö, in relatively mild weather, with temperatures ranging from 0 °C to 9 °C. The outdoor temperature is in itself not very important when it comes to examining how well the natural circulation works in a building. During all tests, the DH supply temperature remained well above 80 °C, which signified that the course of events (the high rise in the secondary supply temperature, etc.) was equivalent to what it would be at a lower outdoor temperature. Nevertheless, it was important to investigate which relative heat loads one can expect during cold weather. Computer simulations were performed using dynamic models built with the software Matlab and the associated toolbox Simulink. By verifying the model with field tests, it could be tuned to give rise to simulations resembling the experimental results. A more detailed description of the model can be found in a previous paper [7].

Figs. 9 and 10 show the results from simulations for two models representing two extremes regarding natural circulation, at various outdoor temperatures. Model 1 resembles a four-storied multi-dwelling building from the 1950’s with a 2-pipe system, 20 flats, and model 2 provides simulations for two six-storied multi-dwelling buildings with a joint substation, 1-pipe system and 100 flats per house. The upper diagrams show the heat supply that can be achieved with natural circulation, relative to the original supply.

![Fig. 7. The most common type of valve group used for DH-connected heating systems.](image)

![Fig. 8. Supply (solid lines) and return (dashed lines) temperatures measured on a valve group during natural circulation.](image)

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and the lower diagrams display the indoor balance temperature ($T_{i,\infty}$), i.e., the indoor temperature achieved after an infinitely long blackout. The ability to enhance the natural circulation by an increased DH supply temperature ($T_{ps}$) was also examined for each simulated outdoor temperature. The temperature was increased to 120 °C (which generally represents the maximum temperature used in Swedish DH systems) and was subsequently reduced to 70 °C for comparison. (One can also imagine that a lower supply temperature could be realistic in a case where only limited production resources are available during a power failure.) For the reference case, the supply temperature that is normally applied in Malmö’s DH network, shown in Fig. 11, was used.

As opposed to model 2, model 1 provided much more favourable results for natural circulation. According to model 1, the
building received 80% of the heat supply, provided that the supply temperature was maintained (i.e., normal for the present outdoor temperature). This means that the indoor temperature should never fall below 13°C. The same temperature was attained with model 2 at an outdoor temperature of approximately 2°C. Regarding the impact of the DH supply temperature on the indoor temperature, an increase of the supply temperature to 120°C at an outdoor temperature of −5°C signifies that the indoor temperature increases by 4°C to over 20°C according to model 1.

Fig. 12 presents the results in a slightly different way. The x-axis presents the current heat load relative the design heat load at DOT.
(design outdoor temperature, −15 °C in Malmö). The y-axis shows the achieved level of heat supply with natural circulation relative to the design heat load at DOT. The solid, diagonal line indicates the necessary relative heat supply in order to achieve an indoor temperature of 21 °C. The dashed line indicates the heat supply needed to achieve an indoor temperature of 5 °C. Authorities in Sweden [21] have identified this level as the lowest acceptable indoor temperature, with the exception of health and elder care activities, for which temperatures below 18–20 °C cannot be accepted. The performed tests are displayed by (●) and as can be seen, all the tested objects achieved a heat supply resulting in an indoor temperature well above 5 °C.

To estimate the level of heat supply by natural circulation at DOT (100% heat load), extrapolated values (▲) were calculated.2 Approximately half of the objects now managed to reach an indoor temperature of 5 °C or more. However, several facts should be kept in mind: Due to the thermal inertia of the buildings, the indoor temperature does not immediately fall to the same level as the outdoor temperature. With a limited heat supply, the temperature in many buildings can be maintained several days before reaching a critical level. Also, the aim when selecting test objects was to capture various types of extremes, not to test a number of similar buildings that belong to the most common ones in the building stock. For example, two of the objects were equipped with the HEX-type with outgoing pipes at the bottom. Without this otherwise rare type of substation, the heat supply during the tests would likely have been significantly higher.

In the other objects that received a low heat supply, the heat was generally unevenly distributed in the sense that it was more or less normal in one part of a building whereas the other part was generally unevenly distributed in the sense that it was more rare type of substation, the heat supply during the tests would likely have been significantly higher.

4. General guidelines to enhance natural circulation

The present work has resulted in a number of recommendations addressed to all concerned parties, i.e., authorities, DH utilities and manufacturers, property owners, operators and residents [10]. The Swedish District Heating Association has modified their recommendations to include that control valves for heating stop in their current position [18].

For the DH utility, it is essential to have back-up power for production and distribution of heat. It is beneficial for the natural circulation to have a supply temperature as high as possible. How high it can be, however, be decided by each DH utility depending on their system’s prerequisites.

The recommendations also include guidelines for house owners how to test or estimate the possibilities for natural circulation in a building as well as measures of how to enhance natural circulation if a power failure occurs (e.g., by opening closed control valves).

5. Conclusions

During a power failure, there exist good opportunities for heat supply by natural circulation in DH-connected space heating systems. The vast majority of control valves remain in their positions and DH water can thus continue to pass through the space heating HEVs. Nonetheless, this is under the condition that the DH network can be operated during a power failure, i.e., that the DH utility has back-up power for production and distribution of heat. In addition, certain customers who have their own back-up power supplies, such as hospitals, depend on the DH network for their heat supply. The obtained results demonstrate that natural circulation can arise in the vast majority of buildings, thus supplying heat equivalently to 40–80% of the current heat supply at low outdoor temperatures. This signifies that it should be possible to cope for several days before a possible evacuation becomes necessary.

Recommendations have been compiled, designed to increase possibilities for natural circulation in different systems, and have been addressed to all concerned parties. The two most important recommendations are: (1) for the DH utility to ensure that they have back-up power for the production and distribution of heat and (2) for building owners to ensure that the control valve for the radiator HEX is not closed in case of a power failure. The first point is essential in order to be able to distribute DH at all, and the second point is essential in order to achieve natural circulation in the radiator systems.

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References

[13.11.07, in Swedish].
[13.11.07, in Swedish].


Adaptive control of radiator systems for a lowest possible district heating return temperature

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Abstract

The present paper describes how the control of a radiator system connected to a district heating network via a heat exchanger can be optimised to provide the lowest possible district heating return temperature. This can be achieved for each operating point by employing an optimal combination of radiator circuit supply temperature and circulation flow rate. The control algorithm gradually creates a modified control curve for the radiator circuit, enabling it to consistently provide an optimal cooling of the district heating water. Since the heat exchanger is dimensioned for very low outdoor temperatures, it is oversized for all other heat loads. In addition, radiator systems are often oversized due to safety margins. Such facts render it possible to reduce the district heating return temperature.

The objective of the present study was to develop a control algorithm and to test it in practice. A description is here given of the algorithm, as well as of field tests that were carried out to practically verify it. The control method could be implemented in any modern control logics for adaptive control of a radiator circuit, and the obtained results indicated that one can expect a lowering of the return temperature in line with previous theoretical calculations.

Keywords: District heating, low return temperature, space heating, radiator system, adaptive control

Nomenclature

Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>constant (-)</td>
</tr>
<tr>
<td>c_p</td>
<td>specific heat (J/kg·K)</td>
</tr>
<tr>
<td>m</td>
<td>mass flow (kg/s)</td>
</tr>
<tr>
<td>Q</td>
<td>heat flow (W)</td>
</tr>
<tr>
<td>T</td>
<td>temperature (°C)</td>
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Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>reference case</td>
</tr>
<tr>
<td>comp</td>
<td>compensated</td>
</tr>
<tr>
<td>damp</td>
<td>dampened</td>
</tr>
<tr>
<td>i</td>
<td>indoor</td>
</tr>
<tr>
<td>o, out</td>
<td>outdoor</td>
</tr>
<tr>
<td>opt</td>
<td>optimal</td>
</tr>
<tr>
<td>orig</td>
<td>original</td>
</tr>
<tr>
<td>p</td>
<td>primary</td>
</tr>
<tr>
<td>r</td>
<td>return</td>
</tr>
<tr>
<td>rad</td>
<td>radiator (system)</td>
</tr>
<tr>
<td>s</td>
<td>secondary, supply</td>
</tr>
<tr>
<td>tot</td>
<td>total</td>
</tr>
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</table>

Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td>Control Valve</td>
</tr>
<tr>
<td>DH</td>
<td>District Heating</td>
</tr>
<tr>
<td>DHW</td>
<td>Domestic Hot Water</td>
</tr>
<tr>
<td>DOT</td>
<td>Design Outdoor Temperature</td>
</tr>
<tr>
<td>Gr</td>
<td>Grädigkeit, difference between primary and secondary return temperatures</td>
</tr>
<tr>
<td>HEX</td>
<td>Heat EXchanger</td>
</tr>
<tr>
<td>TRV</td>
<td>Thermostatic Radiator Valve</td>
</tr>
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</table>
1. Introduction

The present paper demonstrates how the control of a radiator system connected to a district heating (DH) network via a heat exchanger (HEX) can be optimised to provide the lowest possible DH return temperature. This is done by always choosing the optimal radiator supply temperature and flow rate.

1.1. Relevance of the topic

The benefits of low return temperatures are well known in the DH technology. A specific advantage of the control method demonstrated in this paper, as opposed to, for example, conventional low flow balancing, is its robustness, enabling the lowest possible return temperatures to be consistently obtained. This is the case independently of the current outdoor temperature and heat load, even if the DH supply temperature changes, the HEX becomes fouled, or the house heating requirements change. The idea is also to utilise the fact that, since a HEX is dimensioned for an extremely low outdoor temperature, it is in fact oversized for all other (lower) heat loads. In addition, radiator systems are generally also oversized for safety reasons, thus providing further potential to reduce the return temperature.

1.2. Objective

The objective of the study was to develop a control algorithm for determining the optimal choice of supply temperature and flow in an arbitrary radiator system for every heat load in order to minimise the primary return temperature.

1.3. Limitation

The present investigation has dealt with DH substations that were indirectly connected to the DH network, i.e., hydraulically separated by HEXs.

2. Heating system temperatures

2.1. Conventional temperature curves

There exist various ways to control the heat output in a heating system. Such methods can be based on a constant supply temperature combined with local flow control, or a constant flow rate in combination with a supply temperature curve, or both. The control of the flow, or supply temperature, can be based on the feedback (e.g., indoor temperature) and/or the feedforward (e.g., outdoor temperature). Here, we have dealt with the prevailing control method used in Sweden; an outdoor temperature-compensated supply temperature, ensuring that an adequate amount of heat is supplied to the building at each outdoor temperature. The feedforward signal (outdoor temperature) can in certain cases be supplemented by, for instance, the wind speed. The radiators are normally equipped with thermostatic radiator valves (TRVs), of which the main task is to compensate for free heat (e.g., solar radiation, electrical equipment or bodily warmth) by reducing the flow through the radiator.

In order to select the design temperatures of the radiator system, various recommendations have prevailed during different periods and in different countries [10]. Presently, lower temperatures are generally in use (e.g., 60/45°C, 60/40°C or 55/45°C as design temperatures), while higher temperatures have traditionally been employed (90/70°C and 80/60°C). There is a substantial oversizing of the radiator system in general, and of the
radiator surfaces in particular, as presented in both Swedish studies [3], [12] and international ones [5], [8] and [10]. This is due to an overestimation of a building’s heat losses, which also often decrease over time by energy-saving measures. Another reason is that, during the design stage, the components are generally selected in sizes larger than required to ensure safety margins.

If an oversized system - with respect to flow and supply temperature – operates as if it were correctly dimensioned, the indoor temperature would to be too high. For each system, a new control curve must be adapted. What this would look like depends on the magnitude of the radiator flow, among other things. If the radiators are oversized already during the design stage, the circulation pump will be equally oversized. This means, that if the radiator surface is oversized by 100 %, the radiator flow will be twice as large as that required.

An oversized system can be regarded as a properly dimensioned system operating within a higher outdoor temperature range than it actually does. An oversizing of 100% implies a doubling of the temperature range where heating is needed, see Fig. 1. According to the new temperature curve shown in the upper left diagram in Fig. 1, a lower supply temperature can be obtained for each outdoor temperature within the normal temperature range. Since the 80/60°C case occurs at the new, theoretical \( T_{dot} \) (design outdoor temperature, originally set to -15°C), the temperature drop in the radiator system at the real \( T_{dot} \), is only 10°C (55/45°C) instead of 20°C, as a result of the circulation flow rate being 100 % too high.

The upper right diagram shows another case where the required, lower, circulation flow from the dimensioning case is used, corresponding to a temperature drop of 20°C at the actual \( T_{dot} \). In order to avoid overheating, the temperature curves are shifted down so that the heat output is halved as compared to the original case. This signifies a change in the operating conditions to approximately a 60/40°C temperature programme.

Another way to compensate for oversizing is to maintain the supply temperature and reduce the flow even more, as shown in the bottom left graph of Fig. 1. This way, a so-called low-flow system is obtained. In theory, such a case should be achieved automatically if the radiators are fitted with TRVs. However, in practice, the system needs to be hydraulically balanced to avoid imbalance and overheating caused by limitations in the TRV function.
2.2. Optimised temperature programmes

The benefits with regard to the primary return temperature from adjusting the flow according to the heat load are known. The idea of using an optimal combination of flow and supply temperature was conceived by Frederiksen and Wollerstrand [2], and this theory has been further studied [13] [11]. The guidelines from Euroheat & Power [1] state that the lowest return temperature is obtained by varying the flow according to the consumption. If such a variable flow is used, it is controlled by TRVs either in combination with a constant supply temperature or with an outdoor temperature-compensated supply temperature. Langendries [4] suggests a central control of the flow rate through the pump’s rotating speed, but claims that it appears to be a rather difficult and expensive system. Petitjean [9] proposes a lowering of the pump speed at low heat loads, when the TRVs are almost fully open, but finds it problematic to determine which parameter to use for controlling the pump speed.

It should be possible to implement the control algorithm presented in this paper in any modern, state-of-the-art control logics for building automation, which are today often used for controlling DH substations. The control method suggests how the flow can be determined for each heat load. The flow is regulated by adjusting the pump’s rotating speed. Speed-controlled pumps are commonly used nowadays and they provide a superior controllability [1], [10].

Let us first study an example of an optimal control curve for a 100 % oversized system. Such a curve is presented in Fig. 2, which also shows the relative magnitude of the varying radiator flow in relation to the required flow as described above. The blue dashed line in the diagram corresponds to the primary return temperature. For the sake of comparison, the primary return temperature for a 55/45°C system is also shown (gray dashed line).
Fig. 2 Temperatures in a radiator circuit with an optimised temperature curve and a variable flow in a 100-% oversized system. The primary return temperature from a 55/45°C programme is shown for comparison.

Flow-weighted, yearly mean primary return temperatures from the radiator HEX have been calculated with regard to the outdoor temperature duration. Above the dashed line in Table 1, results are shown for a correctly dimensioned system, with an 80/60°C programme as well as with an optimised programme. The gain is estimated to just under two degrees C. The last column shows how the primary return temperature is affected when the length of the HEX is doubled. This comparison can be justified by the fact that the primary return temperature is significantly influenced by the lower secondary flow that the optimisation entails, while the pressure drop and heat transfer rate in the HEX can remain at a magnitude close to the original ones.

Under the dashed line, results are shown for a system that is oversized by 100 %. The first three temperature programmes are identical to those shown in Fig. 1, i.e., 55/45, 60/40 and 80/30°C, whereas the last two are optimised programmes with variable flow.
Table 1: A summary of flow-weighted mean primary return temperatures for various temperature programmes.

<table>
<thead>
<tr>
<th>Oversizing [%]</th>
<th>Temperature programme</th>
<th>Relative flow</th>
<th>Return temperature reduction:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>original HEX</td>
</tr>
<tr>
<td>0</td>
<td>standard, 80/60°C</td>
<td>1</td>
<td>44,9</td>
</tr>
<tr>
<td>0</td>
<td>optimised, load dependent</td>
<td>(0.2-1)</td>
<td>-1,8</td>
</tr>
<tr>
<td>100</td>
<td>55/45°C (high flow)</td>
<td>2</td>
<td>34,7</td>
</tr>
<tr>
<td>100</td>
<td>60/40°C (normal flow)</td>
<td>1</td>
<td>-2,0</td>
</tr>
<tr>
<td>100</td>
<td>80/30°C (low flow)</td>
<td>0,4</td>
<td>-3,2</td>
</tr>
<tr>
<td>100</td>
<td>optimised, load dependent</td>
<td>(0.2-0.5)</td>
<td>-5,9</td>
</tr>
</tbody>
</table>

The following conclusions could be drawn from the table:

- The oversizing of a radiator system leads, in itself, to a significant reduction of the primary return temperature, provided that some kind of compensation has been made in order for the system to work properly, i.e., that an accurate indoor temperature has been provided.
- By optimising the system (through the use of a variable secondary flow), the primary return temperature can be further reduced, especially if the system is oversized.
- By extending the radiator HEX, the return temperature can be further reduced with the temperature programmes that employ a relatively low flow.
- Regardless of the degree of oversizing, a combination of an optimised temperature programme and an extended HEX provides a substantially reduced primary return temperature.

The values presented in the table have been calculated only for the radiator HEX. When considering the substation’s total return temperature, it can be said to be smoothed by the DHW consumption. Calculations corresponding to those in Table 1 for a parallel and a 2-stage substation for 20 flats (based on the Swedish District Heating Association’s recommendations for sizing) result in reductions in the return temperature that are approximately 20 % lower than the values shown in the table. The difference between the parallel and the 2-stage connection is negligible when the return temperature from the radiator HEX is low or moderate, a fact that has been previously demonstrated [6] [3]. Euroheat and Power recommend that a 2-stage connection be used only in large multi-residential buildings if the primary radiator return temperature is high. However, it should not be employed if a low-flow heating system providing low return temperatures is used [1].

The advantage of extending the HEX when the secondary flow is low actually demonstrates the optimisation problem: When the secondary flow is reduced, the secondary...
return temperature will decrease. In the radiator HEX, the situation is different. As the secondary flow decreases, the grädigkeit, i.e., the difference between the primary and secondary return temperatures, increases as a result of the heat transfer coefficient in the HEX being strongly flow dependent. Fig. 3 shows how the secondary return temperature is lowered with a decreasing secondary flow while the grädigkeit increases. This results in a primary return temperature that, at first, decreases and then increases when the secondary flow is further reduced. The values in the figure have been taken from one of the test objects. For this heat load, the lowest primary return temperature was achieved for a secondary flow of approximately 30% of the original flow.

![Fig. 3 Primary and secondary return temperatures, as well as the grädigkeit, as functions of the radiator flow.](image)

Another reason for including the impact of an extended HEX in the comparison in Table 1 is the opportunity of connecting to new installations. Large parts of the housing stock in Sweden, built under strong political incentives during the 1960s and 1970s, are facing substantial renovation needs. The results of this project can be considered consistent even if fewer radiator systems be oversized in the future, whether incorporated in older, renovated, or new buildings. The smaller potential for return temperature reductions resulting from less oversized radiator systems may be compensated by the ability to install a HEX that is dimensioned for of an optimised radiator programme, i.e., a longer HEX. Furthermore, with optimised control, there exists a preparedness for future changes in system temperatures in the DH network. Should the DH supply temperature be changed, an adaptive control will ensure that the lowest possible return temperature is always achieved.

In order to operate according to Fig. 2, the algorithm must combine a control of the radiator supply temperature with a control of the radiator flow as a function of the heat load and the DH supply temperature. In previous work [7], we have shown that it is possible to manually determine the optimal radiator supply temperature and flow. A natural continuation is to develop a method for automatic adjustment of parameter values for the optimal control algorithm.
3. The test objects

The tests have been carried out in four multi-residential buildings in the city of Karlshamn, Sweden. The houses were built in 1967-1968: three of them had three stories and a basement, and one had six stories and a basement. The number of flats varied between 20 and 30 per house.

The radiators in all houses were fitted with TRVs, but these were at least ten years old. It was thus uncertain whether they functioned properly. The circulation flow was found not to vary significantly in any of the radiator circuits, which may have been an indication that many of the TRVs were not working. However, it should be noted that the presented control algorithm is independent of the use of TRVs in a system. Whatever combination of optimal supply temperature and flow that is identified for a given outdoor temperature, the heat supply will be the same. The main task for TRVs is to limit the heat supply in a room where additional heat supply (solar radiation, bodily warmth or electrical equipment) would result in an overheating of the room.

The houses had been connected to the DH network in 2004. The substations were of the 2-stage type and equipped with control logics of the brand IQ Heat (Alfa Laval AB). The equipment for the building automation was manufactured by Siemens and furnished with a separate communications module that could also be used for executing minor computer programmes. There was also an internet connection, rendering it possible to communicate in a number of ways, such as via the software Saphir ScopeMeter© (Siemens), or FTP. After a reconfiguration, the pump speed could be controlled, since all pumps were equipped with communication modules.

In order to monitor the circulation flow in the radiator circuits during the tests, clamp-on ultrasonic flow-meters were utilised. However, the objective was to develop a control algorithm based on modern, state-of-the-art equipment without using additional installations. To assure that the temperatures measured in the substation corresponded to the average temperature levels in the various risers in the radiator circuits, thermocouples and resistance temperature sensors were installed in two of the houses. This enabled measurement errors or disturbances in the radiator circuit to be identified.

A central aspect of the project was for the tests not to have any negative impact on the indoor climate. The indoor temperature could be monitored thanks to six wireless sensors installed in each house in the area. The indoor temperature is merely one indication of thermal comfort, and other factors, such as humidity, radiation and air drafts, were not included in the scope of the project. We confine ourselves by noting that if the indoor temperature was not influenced by the tests, the amount of heat emitted from the radiators had not been affected.

3.1. Modifications in the substations

After some initial tests, the circulation pumps were found to be generally oversized to such an extent that the flow rate could not be decreased as much as desired. There existed a predetermined minimum rotational speed for this type of pump, implying that the speed could be reduced by 60-70 %. Discussions with the manufacturer revealed that the lowest pump speed could not be changed in this model, for which reason the decision was made to throttle the flow with an existing shut-off valve located after the pump, and which shifted the pump’s operating range. The throttling was conducted in order for the pump to give half the flow rate at 100 % rotational speed. The control curve was modified accordingly, leading to
the temperature drop in the radiator circuit becoming doubled and the heat supply remaining unaltered.

We were unable to receive a comprehensive reply from the pump manufacturer with respect to the possible measures regarding the regulation of the pump. A discussion with another manufacturer implied that there were no technical limitations for how far down the pump speed could be controlled. However, such an extension of the manoeuvrable range has so far not been requested. After a simple modification of the pump’s frequency converter, the working range could be extended from today’s 30-100 % to, in an extreme case, 2-100 %.

3.2. Existing control of the radiator circuits

The heat output from the radiators was controlled as a function of the outdoor temperature, which was dampened with regard to the building’s thermal inertia. Assuming that the circulation flow rate in the radiator circuit was more or less constant, one could also assume that the temperature drop in the radiator circuit was proportional to the required heat supply, i.e., to the difference between the balance temperature of the building (where the radiator system ceases to provide heat) and the dampened outdoor temperature. This can be expressed as:

$$\frac{T_{i,r} - T_{i,r}}{T_{balance} - T_{out,dampened}} = \text{constant}$$

The constant can be used to determine $\Delta T_{i, DO} T$ according to:

$$\Delta T_{i, DO} T = \frac{T_{i,r} - T_{i,r}}{T_{balance} - T_{out,dampened}} \cdot (T_{balance} - T_{out, DOT})$$

This relation can be exemplified by measured data from approximately one and half months of operation for all substations within the area. These results are shown in Fig. 4.
The employed control curves provided a relatively stable estimate of the temperature drop at DOT, suggesting that they presented a reasonable fit with the radiator circuit’s heat transfer characteristics. This is important information when modifying these curves under experimental conditions. Although the radiator circuits within the area were designed by the same consultant, there is today a large spread in the choice of control curve and resultant temperature drop. It is likely that the curves have been gradually adapted to the circuits’ hydraulic properties and balancing, and one can assume that this is a common situation.

When older houses are renovated and their radiator circuits are modernised, there are no guarantees that oversizing is taken into consideration. For example, the radiator HEX in a substation that was installed in 2005 in one of the houses was dimensioned for 185 kW heat output at DOT with temperatures corresponding to 80/60°C at a flow of 2.25 l/s. However, when examining data for this substation, it turned out that the substation delivered less than 40 kW at an outdoor temperature around 0°C, which corresponded to a load of approximately 50 %. The actual flow rate was about 1.1 l/s and the temperatures corresponded to 60/40°C, thus representing an oversizing around 100 %.

4. Adaptive optimisation - method

In the theoretical example, the system was assumed to be 100 % oversized, while in an arbitrary system one cannot be sure of the degree of oversizing. It is also desirable to have a robust and adaptive control algorithm. The method found to function the best is described below. This approach consists in gradually modifying, by automatically performed tests, the control curve and determining the associated flow rate.
4.1. Online testing

By locking the control valve (CV), one can assume to have approximately the same primary flow through the radiator HEX, and since the variations in the cooling of primary water is relatively small, the heat supply is also approximately constant. If the secondary flow is reduced while the CV is maintained locked, the temperature of the secondary flow leaving the HEX will rise. When a new flow and its associated supply temperature are tested, the current level of the primary return temperature is compared to the level before the experiment. In this way, the new combination of flow and supply temperature can be either accepted or rejected. This method renders it possible to implement the adaptive algorithm in any arbitrary system, leading to the control curve becoming gradually modified. This method we suggested in [7].

One problem associated with this kind of optimisation is that the method is sensitive to disturbances. If the primary supply temperature, primary differential pressure or the outdoor temperature changes during the test, one cannot be sure that the heat supply is constant. In that case, a reduced return temperature could be the result of a heat supply that is too low. Such tests have to be rejected.

In order to render the tests less sensitive to disturbances, the CV is locked only briefly, in order for the HEX to stabilise. Subsequently, we return to automatic control, but instead of using the control curve, the control aims at maintaining a constant temperature drop in the radiator system. If this is successful, the heat supply is also kept constant. One can assume that the secondary flow is relatively constant: as long as tests are conducted at night, no solar radiation is present and internally generated heat is likely to be at a relatively steady level. If, for instance, the primary supply temperature or differential pressure rises during the course of a test, the CV will close somewhat causing the secondary supply temperature, and thereby also the temperature drop and heat supply, to be detained at the same level.

A test is started by keeping the CV locked for ten minutes. As shown in Fig. 5, this leaves enough time for the HEX to stabilise. In the figure, the flow was reduced at 3:00; with the result that the grädigkeit increased, (the lower flow reduced the heat transfer coefficient in the HEX). The new level of the grädigkeit became stable already after about two minutes. The CV was maintained locked for ten minutes, which should be sufficient even for very low flows and most types of HEXs. Subsequently, the control was resumed in order to ensure a constant temperature drop on the secondary side.
Fig. 5 Temperatures in the radiator HEX when the flow rate is changed.

The temperature drop was controlled by verifying the current temperature drop, e.g., every five minutes, and comparing it with the desired temperature drop, i.e., the temperature that was observed when the CV was locked. If the difference exceeded a certain value, 0.2°C has been used so far, the set-point for the supply temperature was updated according to

$$T_{s,p} = T_{s,r} + \Delta T_{s,p}$$

Fig. 6 displays a performed test: At 1:00 a.m., the CV was locked and the radiator flow rate was reduced from 0.59 to 0.36 l/s with the result that the secondary supply temperature rose from 40 to 44°C. After ten minutes, the temperature drop in the radiator circuit was automatically controlled (in this case, the temperature drop was stable and it took more than 15 minutes before the CV opening degree required adjustment). After ninety minutes, the second flow reduction was carried out, to 0.24 l/s, and the secondary supply temperature increased to about 48°C.

The total primary return temperature varied to a relatively large extent, partly because of tappings of domestic hot water (DHW), but also due to the DHW control in this substation being very unstable when no tappings were made. However, the return temperature from the radiator HEX was of interest for the tests. In this object, the grädigkeit was very small, and even for a low radiator flow, the grädigkeit was below one degree. One can see from the figure that the return temperature had fallen from just under 32°C to slightly over 28°C during the test. This resulted in, for a current outdoor temperature of 8°C, the set-point for the secondary supply temperature being changed from 40 to 48°C while the flow should be reduced from 0.59 to 0.24 l/s.
Fig. 6 Results from a test. The flow was reduced at 1:00 and 2:30. The top graph shows temperatures in the substation, the next graph presents the valve position for heat and DHW, and the last two display the primary (including DHW) and secondary flow and the primary (including DHW) and secondary heat supply, respectively.

An interesting aspect of this test was that the primary supply temperature fluctuated a lot. Since the secondary temperature drop was kept constant, it had no impact on the outcome of the test. One can see that the CV generally demonstrated a lower opening degree later in the night, as opposed to before 1:00, when the primary supply temperature increased. Without the ΔT control, the heat supply would have been too high during the last part of the test.
Regarding the measurement of the heat supply to the radiator system: It was relatively stable during the period when each flow was tested. However, the level of the heat supply decreased in connection with the flow changes. The explanation for this was most likely that the test signal of the clamp-on flow-meter became weaker when the flow decreased. Based on a comparison of the primary side heat supply just before the experiment started, i.e., between 0:50 and 0:55, when no DHW tappings occurred, it was estimated to 23 kW. Also between the hours 3:00 and 3:30, during the second flow reduction, the average heat supply was 23 kW. The reduction of 10 % recorded on the secondary side was not visible on the primary side, which supported the theory with the clamp-on flow-meter malfunction.

The radiator flow was altered by changing the set-point for the pump speed, expressed as a percentage of the maximum speed. It has been found that two flow alterations of ninety minutes each are suitable per test, as this would allow the secondary return temperature to stabilise even at very low flows. The first test for any outdoor temperature, as was the case in Fig. 6, means that starting conditions include the original control curve and flow rate. It is then desirable to perform two fairly large flow reductions since, according to the theoretical calculations, one can expect to find an optimum at a relatively low flow. If, however, the flow is already on a low level, it is reasonable to attempt one slightly higher and one slightly lower flow rate.

If a modified control curve is used before a test is about to start, the control should be interrupted and the pump speed kept constant for an hour prior to the test. This way, one avoids the risk of the flow changing (due to alterations in the outdoor temperature) too close to the test, which could result in unstable radiator system temperatures.

The algorithm for the adaptive control is illustrated by the flow chart in Fig. 7.

In Fig. 8, the test results from Fig. 6 have been supplemented with the indoor temperatures in the building. The thick line represents a mean value of the data from the six sensors in the house in question. The mean temperature was slightly reduced, about 0.2°C, most likely due to the outdoor temperature falling approximately 3°C during the test, while the heat supply was kept constant.
Fig. 7 Flow chart describing the adaptive control algorithm.

Fig. 8 Indoor temperatures during the test shown in Fig. 6. The thick line represents the mean value of the measurements in six flats in the building.
Fig. 9 shows the supply and return temperatures, measured on four of the most remote risers from the substation, during a test. A continuous matching against measurements on risers gives a good indication that the flow distribution in the system was not impaired by the optimisation. The temperature profile was closely matched to the profile at the substation. Both flow reductions resulted in increased temperature drops.

Fig. 9. The results of measurements on risers in the basement.

4.2. Updating the control curves

After the completion of a test, the obtained information needs to be evaluated. The influence of the variation of the outdoor temperature is not entirely obvious; its influence decreases with an increasing time constant for the building. Variations on the primary side normally have is compensated for since the heat supply is kept constant. As a result, it is sufficient to verify that the heat supply was maintained at a steady level during the test, avoiding any disruptions.

If a test result is accepted, the primary return temperatures for each tested flow are compared in order to verify which flow resulted in the lowest return temperature. This flow also gave rise to a secondary supply temperature. It is however not obvious how to read this temperature, given that it was regulated by the controller and changed continuously. The most logical choice is to read the mean value at the end of the test period, before the pump speed changes. At this point, one could expect a stable secondary return temperature, e.g., during the last five minutes. In addition to the secondary supply temperature, also the dampened outdoor temperature, i.e., the input signal to the controller, is recorded when the CV is locked for the first time. The reason for this is that the heat supply is subsequently kept constant - at a level matching the outdoor temperature (and heat load) at the time before the test was started.

The next step consists in using the information attained from the test to modify the control curves. Initially, the original curve was used and the pump was, in our case,
controlled to give a constant differential pressure. If the result of a test is that a lower primary return temperature is obtained at a lower secondary flow rate, the control curve is updated for that outdoor temperature. A reasonable resolution is 1°C. The original control curve, generally based on 5-8 points, was therefore initially extended to comprise values for each outdoor temperature.

If the experiment, as in Fig. 6 above, was performed at 8°C, this point on the curve would be updated. Along with the new supply temperature there followed a new radiator flow, which in our case was expressed as a new set-point for the pump speed.

The adaptive control continues in this manner night after night, and the control curves are continuously updated. Outside the test periods of approximately three hours each night, the modified control curves are used for controlling the heating system.

Fig. 10 shows an example of the gradual development of the modified control curve. The first graph shows a new point at 0°C (used for 0 ± 0.5°C). In the second (upper) graph, a point for 3°C has been added, while the range 0 to 3°C is complete in the third. The fourth graph shows a much more complete control curve (-5 to 10°C). Temperature curves corresponding to constant flow systems with lower flows than the original system have been included as thinner lines. The value for 10°C coincides with the curves of a system with a low flow, while the value of -5°C coincides with the curves of a system with a moderately reduced flow (normal flow). The last graph clearly demonstrates that the modified curves are based on a variable flow, i.e., they coincide with various constant flow curves at different points.

![Graph showing modified control curves](image)

**Fig. 10** A stepwise modification of the control curve. The supply temperatures are drawn in solid lines while the returns are dashed.

As shown in the second graph of Fig. 10, the modified curve could emerge in sections that subsequently are combined. One way to speed up the modification of the control curves
is to interpolate intermediate values rather than wait for a flow optimisation at the missing outdoor temperature. Even the return temperatures could be interpolated, since it is possible to determine the required radiator flow for a known temperature drop (and heat supply).

For the first test to be carried out at a specific outdoor temperature, it is logical to let the results of this test fully replace the original points on the curve. As more tests are performed for the same outdoor temperature, one can proceed in several ways. Since the control should be adaptive and thus able to take into account changing circumstances both in the DH network and in the building, the results of new tests should be employed. However, one may expect that tests performed close to one another in time, at equivalent outdoor temperatures, still provide slightly differing results for varying reasons. A solution would therefore be to use a forgetting factor, i.e., to gradually "forget" old values when the supply temperature curve is updated with new data. A possible approach for doing so consists in calculating the new supply temperature, \( T_{s,i+1} \), as a mean value of the obtained, \( T_{s,i,test} \), and the last used, \( T_{s,i,n-1} \), supply temperature according to:

\[
T_{s,i,n} = \frac{T_{s,i,test} + T_{s,i,n-1}}{2}
\]

When a new test is performed at the same outdoor temperature, a new mean value is calculated, which means that older values will have less and less influence. To determine the secondary flow associated with the new supply temperature, i.e., the one providing the correct heat supply at the current outdoor temperature, the expected temperature drop is calculated as:

\[
\Delta T_{r,n} = T_{r,i,n} - T_{r,i,n-1}
\]

where \( T_{r,i,n} \) is determined in analogy with \( T_{s,i,n} \), according to:

\[
T_{r,i,n} = \frac{T_{r,i,test} + T_{r,i,n-1}}{2}
\]

To ensure that the heat supply is kept constant, the required flow for the new temperature drop is calculated. Since the flow is inversely proportional to the temperature drop \((Q = \frac{c_p \cdot m \cdot \Delta T}{\eta})\), it can be determined from the last used flow and temperature drop, together with the new temperature drop, according to:

\[
\dot{m}_{r,n} = \frac{(\dot{m}_{r,n-1} \cdot \Delta T_{r,i,n})}{\Delta T_{r,i,n}}
\]

As mentioned earlier, the flow rate is set by changing the set-point for the pump speed. According to the affinity laws for fluid machines, the flow is proportional to the rotational speed. The process of letting the last modified supply temperature and the result of a new test form a new modified supply temperature is illustrated in Fig. 11.
Fig. 11. An approach for modifying the control curve based on new test results.

The proposed method for updating the control curves indicates that if for instance the DH utility demonstrates a long-term change in the supply temperature in the network, the control system gradually adapts to the new temperature. However, there are always variations in the primary supply temperature. This may include both unintended and intended variations which may be the result of, for example, a charging of the network if the outdoor temperature is expected to fall. Since the primary supply temperature affects the primary return temperature, it is desirable for the adaptive control to also compensate for such short-term variations. One way of doing so is to develop a number of parallel control curves for various intervals of the primary supply temperature. If the temperature is greater than a certain level, an alternative control curve is employed, whereas if it is below a certain level, one utilises another. This method has yet to be tested and there is no basis for assessing how much impact one can expect from normal variations in the supply temperature or what would constitute reasonable intervals for parallel control curves in this case. Another variant could be to perform a linear adjustment for the secondary supply temperature depending on the primary supply temperature, according to:

\[ T_{s,s} = T_{s,s,0} \left( 1 + a \left( T_{p,s,0} - T_{p,s} \right) \right) \]

where \( a \) is a constant that can be determined from tests.

4.3. Regarding the measurement of temperatures and flows

Regarding the temperature measurement in the substation, supply and return temperatures on both the primary and the secondary sides are required. One should keep in mind that, on the primary side, the return temperature from the radiator HEX is needed since the total return temperature is affected by the DHW system. This temperature is normally available in modern substation control equipment.
Since the intention is to regulate the secondary flow, it is necessary to have control of it. However, it is desirable to avoid installation of a flow-meter in the secondary circuit. In the tested buildings, flow-meters of clamp-on type have been used to enable a complete control of the tests, and the potential to use the existing energy-meter has also been investigated. The difference between the secondary and the primary side, where the energy-meter is located, is that, on the latter, the total primary flow and the total temperature drop in the substation are measured and the energy required for DHW provision is thus included. Since the tests are performed at night, DHW tappings can be avoided to a large extent. However, energy is still required to compensate for the heat losses from the DHW re-circulation. The size of this loss is, however, relatively easy to determine. By closing the DHW CV for a short time, the primary flow passes exclusively through the radiator HEX. By comparing the average level of heat supply with a closed valve to the level prior to closing the valve, the loss can be estimated. Another comparison once the valve is reopened renders it possible to verify that no tappings occurred while the valve was closed. If the total primary return temperature was not stable, tappings have occurred. When the heat supply to the radiator circuit is known, the radiator flow can be determined.

In the test objects, indoor temperature measurements were used to verify that the adaptive control was able to give the correct indoor temperature. However, one can in fact be sure that the correct amount of energy is transferred to the system for each operating point, regardless of whether the original control curve or the optimised curve is used. A possibility is that there is an imbalance in the system. For example, the most distant riser may not receive the required flow because of a too low differential pressure when the pump speed is decreased. It is, however, more likely that a better balance in the system is achieved when the differential pressure is lowered - this since the pressure losses in the system decreases and all risers receive a more similar differential pressure. However, one must be on the look-out for errors (e.g., short circuits) in the systems - a problem that is often emphasised in connection with low-flow systems, as these tend to be more sensitive to hydraulic imperfections [12].

4.4. Reduction of the primary return temperature

To estimate a yearly mean return temperature reduction (as presented in Table 1) achieved by the adaptive control, an entire, or a major part of the, heating season needs to be evaluated. The control method presented in this paper was developed during the winter and spring of 2009, and only a limited number of tests were performed during the spring. However, Fig. 12 shows the obtained primary return temperature that was attained for the tests that were performed in one of the houses. Note that these results were “first runs” for each outdoor temperature (i.e., the flow was reduced to approximately 40 %), signifying that no further optimisations were undertaken. The curve displaying the original return temperatures was based on the average return temperatures from the radiator system prior to any of the modifications (i.e., for the tests or the constant flow rate change, as described in section 3.1).
5. Conclusions and discussion

An adaptive control algorithm was developed in order to minimise the DH return temperature. The control algorithm can be implemented in any modern control logics for building automation. Some refinement may be done by compensating for short-term temperature variations in the DH network.

During the field studies, limitations in the speed control of the circulation pumps have presented a complication. A modification of the pump’s frequency converter could increase the working range.

There was not enough time to develop completely modified control curves for the test objects during the present heating season. On the other hand, a control curve with an adaptive controller is never definitive; rather it increases as more operational points (different outdoor temperatures) are added and is then gradually modified if outer conditions change.

In order to receive values for the primary return temperature on a yearly basis using the adaptive control algorithm, the new control curve needs to be modified for the entire temperature range. During the performed field studies, the reduction of the primary return temperature was about 3°C. Even though the test period limited the number of performed tests, the temperature range was still rather wide, including temperatures from -2 to 14°C.

It is plausible that certain circuits are more suitable for a variable flow rate, e.g., depending on hydraulic balancing. It would also be possible to map out under which circumstances other heat emitters than radiators, such as fan coil heaters, can be included in a radiator circuit where the flow varies.
References


