IMPROVED COOLING OF DISTRICT HEATING WATER IN
SUBSTATIONS BY USING ALTERNATIVE CONNECTION SCHEMES

Per-Olof Johansson, Per-Olof.Johansson@energy.lth.se
Patrick Lauenburg, Patrick.lauenburg@energy.lth.se
Janusz Wollerstrand, janusz.wollerstrand@energy.lth.se
Dept. of Energy Sciences, Faculty of Engineering, Lund University, Sweden

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 connected 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 levels in the space heating system, when no tapping occurs 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 connections

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 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 connections.

Space heating and provision of domestic hot water (DHW) is characterised by a variation of temperature levels which provides a basis for lowered DH 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 constructed in a way that is optimal for the cooling of DH 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 program of typically 80/60°C (secondary supply/return) or 60/40°C at design outdoor temperature (DOT). However, previous works show that oversizing of heating systems is common, meaning 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 with reduced convection have led the way for building-integrated heating systems such as underfloor heating, working at drastically 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, many bathrooms are instead 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 the lowest possible DH 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) is set to 60 and 40%.

2. CONSTRUCTION OF DH SUBSTATIONS

Figure 1 below shows two common types of 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 represented for an outdoor temperature of 8°C (the average annual temperature in Malmö, Sweden) and a radiator system designed for a 60/40°C temperature program. 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](https://via.placeholder.com/150)

Figure 1. 2-stage (left) and parallel (right) connected DH substations with median temperatures level at Tout = 8°C and 60/40°C design temperature (60 flats). Temperatures are given in °C.

In some parts of Sweden, a 3-stage connection scheme is still rather common, but is generally not installed any longer. 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 great 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 tapped and around 35°C when DHW is tapped. Given that the supply temperature to a heating system, at least for low-temperature systems, mostly is below this temperature level, it would 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 DH water leaving the AH or DHW HEX is always hotter than 50°C when no DHW is tapped.

The matter of various connection schemes in DH substations has been dealt with by different authors 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 probably 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 the 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 which of them gives 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, the primary DH water used for DHW circulation is directed into the radiator HEX during parts of the time.

![Figure 2. R3-stage connected DH substations.](image)

The idea with the R3-stage connection scheme is to cool the DH 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 mass \(m_p\) flow 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 \(m_p\) through the AH. After leaving the AH, the \(m_p\) continues through the RAD HEX, during heating season. If the desired heating system supply temperature level is not reached, valve R1 opens and allows more \(m_p\) to mix with the \(m_p\) 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 \(m_p\) passes through the PH. Below, these control strategies are explained in a different way:
The idea with the series connection is the same as with the R3-stage connection, i.e. to utilize the DH water’s rather high temperature after the DHW HEX when there is no tapping. 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 varies between two operating modes, depending on whether DHW is consumed or not.

The primary DH water supplying the DHW HEX is always led into the radiator HEX when no DHW tapping occurs. 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 DH water. When DHW is tapped, the valve R2 will open, and the substation will work as a regular parallel-connected substation and the radiator HEX is supplied with DH 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. MODELLEING THE DH SUBSTATION AND HEATING SYSTEM

The mathematical description of 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 tapping (tap frequency and tap length) are simulated based on statistical measured data for different number of residential flats. The tapping patterns are simulated based on a program described in [15]. The heat load is assumed to be 3 kW per flat at design outdoor temperature, $T_{DOT}$, (assumed 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.

![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 apartments on the right.](image)

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 program is a low-temperature radiator program 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 programs for the heating systems are shown in Figure 5.

![Figure 5. Different temperature programs for the heating system. Blue lines show corresponding return temperatures.](image)

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

$$T_{pr} = \frac{\sum T_{pr} \cdot \dot{m}_p}{\sum \dot{m}_p}$$  \hspace{1cm} (1)

4. RESULTS

4.1. Residential buildings

Figure 6 shows the primary annual average return temperature for residential buildings. Each diagram shows results for different connection schemes for a specific radiator temperature program 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 programs. However, a parallel connection scheme with DHW preparation 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 DH 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 if the DHW preparation is not 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 and parallel with PH/AH connections, except for the 55/45 program (and to some extent 60/40) where 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 program.](image)

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 are either better, worse, or equal.
Table 1. Results from simulations. A reduction of $T_{pr} > 1^\circ C$ is indicated by ‘−’, a reduction between 0.3-1°C ‘(−)’. An increase in $T_{pr}$ of > 1°C is indicated by ‘+’, an increase between 0.3-1°C ‘(+’)’. Changes less than 0.3°C are indicated by ‘∼’.

<table>
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<th>P3-stage</th>
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<th>Series</th>
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<th>Series with PH/AH</th>
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4.2. Non-residential buildings

There are obviously many buildings connected to DH that 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 probably much smaller than in a residential building of the same size (less showers, cooking etc.) Therefore, simulations with a reduction of 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 programs are 60/40, 55/45 and 40/30°C, see Figure 7.
As seen in the figure, the 2-stage connection scheme and the parallel scheme, both with and without DHW preparation divided into PH and AH, give about the same primary return temperatures. 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 3-4°C depending on the radiator temperature system.

With a reduction of the amount of tapping with 50%, the gain with the series connection and the R3-stage connection is even better; 4-6°C, see Figure 8.
Figure 8. Three different temperature programs with reduction of the number of tapping with 50%.

7. DISCUSSION AND FURTHER STUDIES

DH substations that increases the cooling of DH water is favourable to the DH utility and in many cases also for the DH customer when DH prices are based on both energy consumption and cooling of DH water.

At all load conditions, the simple parallel connection scheme is the poorest. The R3-stage connection scheme always gives the lowest primary return temperature. However, this connection scheme demands 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 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.

For non-residential buildings with less DHW consumption, the series connection and the R3-stage connection gives DH 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


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