Thermal stability and heat transfer in the reservoir low-temperature network

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Abstract. We investigate two properties of a new low-temperature network topology, the reservoir low-temperature network. We show (i) that the maximum heat transfer rate between the load loop and the main mesh occurs when the volume flow in the load loop equals the volume flow in the main mesh and (ii) that temperature fluctuations in the main mesh are dampened when the volume flow in the load loop exceeds the volume flow in the main mesh. The maximum possible damping depends only on the volume flow through the main mesh and the water volume contained in the load loop.

1. Introduction

Low-temperature networks are district heating and cooling networks with network temperatures typically below 20 °C. As cooling demand will increase with global warming in the future, the cooling component will become more important. In low-temperature networks, cooling is achieved directly using heat exchangers. The heat generated by cooling is used by heat pumps, which increases the overall efficiency of the thermal network. Furthermore, low temperature networks allow for incorporating environmental heat sources with moderate temperature levels such as geothermal heat, lakes, ground water and also waste heat from industrial processes. Substituting fossil fuels by environmental heat sources reduces CO$_2$ emissions, which is a key goal of the research program Swiss Competence Centers for Energy Research, Future Energy Efficient Buildings and Districts (SCCER FEEB&D) [1]. However, simultaneous heating and cooling challenges conventional district heating topologies and within the research carried out for the SCCER FEEB&D, a new network topology was developed: the reservoir low-temperature network RLTN [2].

The RLTN consists of a main mesh, in which water is continuously circulated by a main pump. Heat producers and consumers (loads) extract water from the main mesh, circulate this water in their individual load loops and finally return the water into the main mesh. The load loops share a common bypass with the main mesh and are aligned in series along the main mesh (figure 1a), which distinguishes the RLTN from conventional networks with a parallel setup [3]. The first RLTN is planned at the lakeshore of Lake Ontario in Toronto [4].

In this work, we study the influence of the adjustable volume flow in the load loop (i) on the heat transfer rate from the load loop to the main mesh and (ii) on the temperature fluctuations in the main mesh. The heat transfer rate should be maximized when the load is an environmental heat source. If the load is another thermal network, for example a second mesh, the heat transfer rate may be chosen to...
balance heat extraction and heat supply in both meshes. The control of temperature fluctuations is important when the average temperature of the main mesh approaches freezing temperature in winter. For example, temperature fluctuations that fall below 0 °C may cause heat pump failure or even heat pump damage, even though the average temperature is above 0 °C. Decreasing the magnitude of such fluctuations thus ensures robust network operation at temperatures close to the temperature operation limits.

2. Modell setup

The model calculations are carried out using the Dymola simulation environment [5] based on the Modelica standard library [6] as well as libraries developed within the IBPSA Project 1 [7]. These tools allow dynamic hydraulic and thermal simulations of the district heating networks and adjustment of the model complexity depending on the requirements.

The simulation model consists of a main mesh in which the water is circulated by a main pump with volume flow $V_{m'}$ (m$^3$s$^{-1}$) (figure 1). Various load loops with individual loads are connected in series to the main mesh and share a common bypass with the main mesh. In our analysis, we only consider one load loop (framed in figure 1a and shown enlarged in figure 1b), which receives the temperature $T_{m,\text{in}}$ (K) and volume flow $V_{m'}$ from the main mesh (figure 1b). The temperatures into the load and out of the load are $T_{l,\text{in}}$ (K) and $T_{l,\text{out}}$ (K), respectively. The water content of the load loop is $V_l$ (m$^3$). The temperature in the main mesh after the load loop is $T_{m,\text{out}}$ (K).

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Schematic drawing of the RLTN, which consists of a main mesh in which the water is circulated by a main pump with volume flow $V_{m'}$ and various load loops with individual loads connected in series to the main mesh. a. Overview of the main mesh and the load loops. b. Detailed illustration of the section highlighted in (a). c. Types of the load in (b) implemented in simulation models.

Four different models (figure 1c) are used for the load, depending on the study case. The model “constant temperature supply” (figure 1c1) is an infinitely large water volume at predefined temperature $T_l$ (K). This ensures constant $T_{l,\text{out}}$ independently of $T_{l,\text{in}}$ and $V_l'$ and hence represents as a very simplified heat source. The model “heat exchanger” (figure 1c2) is a coil heat exchanger combined with an infinitely large water tank of temperature $T_l$ (K). In this case the heat transfer rate from the load loop to the main mesh depends also on the properties of the heat exchanger. The models “constant temperature
supply” and “heat exchanger” are used to study the heat transfer rate from the load to the main mesh. To study the temperature damping capability of the load loop in the main mesh, we consider two more models. In the model “fully mixed volume” (figure 1c3) the load loop is a fixed volume $V_l$ at homogeneous temperature $T_l$. Any water entering the load with $T_{l,in} \neq T_l$ is instantaneously mixed with the water of the load to a new temperature $T_l = T_{new}$ and $T_{l,out}$ instantaneously adapts to $T_{new}$. In the model “plug flow pipe” (figure 1c4) no mixing occurs. Any water of temperature $T_{l,in} = T_{new} \neq T_l$ entering the load gradually propagates through the load and after the propagation time $V_l/T_l$, the output water of the load changes its temperature $T_{l,out}$ to $T_{new}$. This model may be interpreted as a stratified tank of volume $V_l$.

3. Simulations and results

3.1. Heat transfer rate from the load loop to the main mesh

The heat transfer rate $Q'$ (W) from the load to the network (figure 1) is

$$Q' = \rho c_p V_l' (T_{l,out} - T_{l,in})$$

(1)

Here $\rho = 1000$ kg m$^{-3}$ is the density of water and $c_p = 4182$ J kg$^{-1}$ K$^{-1}$ is the specific heat capacity of water. For $V_l' \leq V_m'$ follows $T_{l,in} = T_{m,in}$ and (1) becomes

$$Q' = \rho c_p V_l' (T_{l,out} - T_{m,in})$$

(2)

For $V_l' > V_m'$, $T_{l,in} \neq T_{m,in}$, because mixing occurs at point I (figure 1b). The heat balance at point I is

$$(V_l' - V_m') T_{l,out} + V_m' T_{m,in} = V_l' T_{l,in}$$

Solving for $T_{l,in}$ and inserting $T_{l,in}$ in (1) results in

$$Q' = \rho c_p V_m' (T_{l,out} - T_{m,in})$$

(3)

Comparing (2) and (3) shows that the smaller of the two volume flows $V_l'$ and $V_m'$ of the load loop and the main mesh, respectively, is relevant for the heat transfer rate.

For the model “constant temperature supply” (figure 2, blue line) we used constant $V_m' = 10$ m$^3$ h$^{-1}$, constant $T_{m,in} = 10$ °C and constant $T_{l,out} = 14$ °C. In order to determine $Q'$ as function of $V_l'$, we varied $V_l'$ between 0 m$^3$ h$^{-1}$ and 20 m$^3$ h$^{-1}$. For $0 < V_l' \leq V_m'$, $Q'$ linearly increases with $V_l'$. For $V_l' > V_m'$, $Q'$ is constant. Increasing $V_l'$ to larger volume flows than $V_m'$ does not further increase $Q'$. In this model $V_l' = V_m'$ is the optimum choice of the load loop flow as it provides maximum heat transfer rate at lowest electricity consumption of the load pump. The result obtained in the Dymola-Simulation is identical to the analytical solutions (2) and (3) (blue solid line in figure 2).

For the model “heat exchanger”, we also used constant $V_m' = 10$ m$^3$ h$^{-1}$ and $T_{m,in} = 10$ °C. At design conditions, defined at $V_l' = 10$ m$^3$ h$^{-1}$, $T_{m,in} = 10$ °C and $T_l = 20$ °C, the temperature difference $T_{l,out} - T_{l,in}$ across the heat exchanger is 4 K. The heat exchanger characteristic (figure 2, red dotted line), obtained by keeping $T_{l,in} = T_{m,in}$ constant at 10 °C and varying $V_l'$ shows the typical behavior of increasing $Q'$ with increasing $V_l'$. However, in reality, for $V_l' > V_m'$ mixing occurs at point I (figure 1b) and consequently (3) applies. With increasing $V_l' > V_m'$, $T_{l,in}$ decreases due to mixing at point I. This also decreases $T_{l,out}$ and consequently $Q'$. By replacing the model “constant temperature supply” by the more realistic model “heat exchanger”, $V_l' = V_m'$ remains the point of the maximum $Q'$, but for $V_l' > V_m'$, $Q'$ now decreases. Large volume flows $V_l'$ thus have negative effect on the heat transfer rate.
3.2. Damping temperature fluctuations in the main mesh

We study the damping of temperature fluctuations by modelling the step response of a temperature front. Initially, all temperatures $T_{m,in}$, $T_{l,in}$, $T_{l,1}$, $T_{m,out}$ in the system are equal to $T_0 = 10$ °C. The volume flow $V_{m}'$ in the main mesh is, as before, kept constant at $V_{m}' = 10 \text{ m}^3 \text{ h}^{-1}$ and the volume $V_l$ of the load is $V_l = 10 \text{ m}^3$. At time $t = 0$, $T_{m,in}$ increases abruptly to 15 °C, forming the step-function input (dashed blue line in figure 3).

We first consider the model “fully mixed volume” (figure 1c3). In this model, the outflow temperature of the load $T_{l,out}$ is related to the inflow temperature $T_{l,in}$ by the energy conservation equation

$$\rho c_p V_l \frac{dT_{l,out}}{dt} = \rho c_p V_l' T_{l,in} - \rho c_p V_l' T_{l,out}$$  \hspace{1cm} (4)

Equation (4) states that the thermal energy of the load (left hand side) changes over time when the thermal energy of the inflow differs from the thermal energy of the outflow. Note that in this model $T_{l,out} = T_l$ by definition of the model. The solution of the differential equation (4) is

$$T_{l,out} = T_0 e^{-\frac{t}{\tau_l}} + T_{l,in} (1 - e^{-\frac{t}{\tau_l}})$$  \hspace{1cm} (5)

Here, $\tau_l = V_l/V_l'$ (s) is a time constant describing the residence time of the water in the load and $t$ (s) is time. The time constant $\tau_l$ is a measure for the damping. The larger $\tau_l$ the stronger is the smoothing of the step function and the stronger the damping effect on temperature fluctuations. The time constant $\tau$ is large for large volumes $V_l$ of the load and for small volume flows $V_l'$ through the load.

In our case, we are not interested in the relation between $T_{l,in}$ and $T_{l,out}$ but in the relation between $T_{m,in}$ and $T_{m,out}$. Equation (4) then changes to

$$\rho c_p V_l \frac{dT_{m,out}}{dt} = \rho c_p V_{m}' T_{m,in} - \rho c_p V_{m}' T_{l,out}$$  \hspace{1cm} (6)

and the solution becomes

$$T_{m,out} = T_0 e^{-\frac{t}{\tau_m}} + T_{m,in} (1 - e^{-\frac{t}{\tau_m}})$$  \hspace{1cm} (7)
with $\tau_m = V_l/V_m'$. Equation (7) is identical to (5) with $V_l'$ replaced by $V_m'$. Consequently $T_{m,out}$ does not depend on the volume flow through the load $V_l'$. The time constant $\tau_m$ and thus the strength of the damping only depends on the volume $V_i$ of the load and the volume flow $V_m'$ through the main mesh. In figure 3, equation (7) is shown as the violet dotted line with parameters $V_i = 10 \, m^3$ and $V_m' = 10 \, m^3 \, h^{-1}$.

In reality, the flow through the load is rather of the plug-flow type (figure 1c4) than completely mixed (figure 1c3). In the case of plug-flow, temperature variations in the water are transported with the flow and no mixing occurs along the direction of the flow. For $V_l' = V_m'$ the step function of $T_{m,in}$ is thus transported from $T_{m,in}$ to $T_{l,in}$ and after the time $V_l/V_l' = 1 \, h$ received by $T_{l,out}$ and $T_{m,out}$ (red dash-dotted line in figure 3). For $V_l' > V_m'$, the temperature received by $T_{m,out}$ transforms from a step function to a gradual increase (green-dotted line and black line in figure 3). The black line in figure 3 represents $V_l'$ being 15 times larger than $V_m'$ and is almost identical to the violet line in figure 3, which was derived using the model “fully mixed volume”. For large $V_l'$ the step response of the model “plug-flow pipe” thus converges to the model “fully mixed volume”.

![Figure 3. Step response for various load scenarios. The blue dashed line represents the input temperature step from the main mesh before the load loop and the other lines represent the temperature responses into the main mesh after the load loop.](image)

4. Discussion
In the investigation of the heat transfer rate from the load loop to the main mesh, we considered only two simplified models of the load, namely the “constant temperature supply” model and the “heat exchanger” model. In reality, however, when the load is a seasonal storage (for example, a geothermal borehole), physical and technical properties as well as the storage dynamics should be considered, which can influence the heat transfer rate from the load loop to the main mesh.

The ability to reduce temperature fluctuations strongly depends on the volume contained in the load loop and thus is a unique characteristic for the RLTN. Knowing the volume of the load loop and the volume flow in the main mesh, the maximum possible damping can be estimated directly. In this study, however, we considered the load as a volume of uniform initial temperature. In reality, the damping effect of the load loop is superimposed with the heat transfer in the load that might lead to additional dynamics that are not considered here.

5. Conclusion
In this work, we studied two effects of the adjustable volume flow in the load loop of a reservoir low-temperature network (RLTN). The first effect is the heat transfer rate from the load loop to the main mesh. The heat transfer rate increases with the volume flow in the load loop until the maximum heat
transfer rate is reached when the volume flow in the load loop is equal to the volume flow in the main mesh. Further increasing the volume flow through the load loop decreases the heat transfer rate.

The second effect is the damping of temperature fluctuations in the main mesh. A temperature front approaching in the main mesh is smoothed by the load loop if the volume flow through the load loop is larger than the volume flow through the main mesh. For large volume flows through the load loop, the step response of the “plug-flow-model” converges against the step response of the “fully-mixed-volume-model”. The step response thus depends only on the volume flow through the main mesh and the water volume in the load loop and can easily be calculated.

In summary, equal volume flows in the load loop and the main mesh ensure maximum heat transfer. However, when a constant temperature in the main mesh is required large volume flows through the load loop stabilize the temperature in the main mesh. This operation mode may be chosen, when the average temperature in the main mesh approaches freezing temperature in winter or the limit for direct cooling in summer. During those times, a decrease in the heat transfer rate and an increase of pumping power may be accepted in favor of robust operation.

6. Future work suggestions
In order to be able to apply the results of the study in practice, we suggest to consider real loads (for example geothermal boreholes) with real heat exchangers and realistic operation conditions, such as realistic load profiles and temperature levels in the main mesh and in the load loops. It is also important to study the interaction between the load loops, since load changes influence the temperatures in the main mesh, which are received by the next load loop. Based on these results guidelines for planners may be developed.

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