Optimization of low-temperature networks by new hydraulic concepts

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Optimization of low-temperature networks by new hydraulic concepts

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Abstract. Low-temperature thermal networks enable simultaneous heating and cooling of buildings and reduce CO₂ emissions by substituting fossil fuels by environmental heat sources. In this work, we compare two different network topologies, the traditional low-temperature network (TLTN) and the new reservoir low-temperature network (RLTN). We show that the volume flow in the RLTN can be adjusted to increase the efficiency of heat pumps and to reduce hydraulic power losses in the supply lines without compromising heat demands.

1. Introduction
With global warming and the resulting heat island effects in urban areas, cooling of buildings will become more and more important in the future [1,2]. Countries with an intense heating period in winter and a moderate cooling period in summer will approach more balanced demands of heating and cooling in the future and thermal networks that enable simultaneous heating and cooling will thus become more attractive. In Switzerland, heating demand is, on average, larger than cooling demand [1,2]. In low-temperature networks with temperatures typically below 20 °C, heat sources can have moderate temperature levels and are typically environmental heat sources such as lakes, ground water, geothermal heat or excess heat from sewage, data centers and industrial processes. Low-temperature networks consequently do not rely on fossil fuels and can be operated emission free. Such networks are therefore in line with the Swiss Energy strategy and the goals of the Swiss Competence Center for Energy Research, Future Energy Efficient Buildings & Districts (SCCER FEEB&D) [3].

Low-temperature networks providing both heating and cooling require new hydraulic concepts [4]. In traditional low-temperature networks (TLTNs), the loads are hydraulically connected in parallel to the network lines (Fig. 1a). A central circulation pump (main pump) supplies warm water from the source to the loads and after heat extraction, the cooled water is transported back to the source. Throttling valves regulate the required volume flows through the loads. TLTNs can also be operated with decentralized circulation pumps at the loads [5–7]. Networks with decentralized circulations pumps consume about 1 % to 5 % less electric energy compared to systems with centralised circulation pumps, depending on the yearly profiles of heating and cooling demand [8].
In this work, we compare the TLTN to a new network topology, the reservoir low-temperature network (RLTN) [9]. In the RLTN, a main pump of adjustable volume flow continuously circulates water in a loop, which is called the main mesh (or “reservoir”). Each load also circulates water in its own load loop using its own load pump. The main mesh and the load loops share a common bypass which allows for heat transfer between main mesh and the load loop [10]. Because there is close to zero pressure loss in the bypass, the main pump and the load pumps are hydraulically decoupled. The first realization of an RLTN is planned at the Toronto Quayside district in Canada [11].

Here, we compare the TLTN and the RLTN in a simplified district with one heat source and four loads with identical heating demands. We first define the boundary conditions for the calculations and then compare the electricity consumption of the heat pumps and the hydraulic power losses in the main mesh in both topologies for a steady state.

![Figure 1. Schematics of the TLTN (a) and the RLTN (b). In both networks, a source S produces water of temperature \( T_{s,\text{out}} \) at volume flow \( V_i' \) (green). The main pump transports the water through the main mesh (magenta) at volume flow \( V_m' \). In the TLTN, the main pump also transports the water through the loads. In the RLTN, each load has its own load pump, which circulates water in the load loop. The main mesh and load loops share a common bypass (c). Mixing points are indicated by blue-red dots.](image)

## 2. Boundary conditions for the comparison

In both networks a source \( S \) (e.g. a data center, industrial waste heat, sewage water or an environmental heat source) produces heat. Here, we assume that the source produces a constant output temperature \( T_{s,\text{out}}(K) \) at constant volume flow \( V_i'(m^3 \text{ s}^{-1}) \). In the main mesh, the main pump circulates water of volume flow \( V_m'(m^3 \text{ s}^{-1}) \). All loads have the same constant heating demand \( Q' \) (W). The heat is supplied by heat pumps, which extract the thermal power \( Q_i' \) (W) at temperature \( T_i(K) \) on the evaporator side of the heat pump from the network and supply the thermal power \( Q' \) at temperature \( T_h(K) \) on the condenser side for heating purposes. The index \( i \) varies from 1 to 4 according to the four loads \( L_1 \) to \( L_4 \). The temperature lift from \( T_i \) to \( T_h \) is realized by the compressor of the heat pump, which consumes the electric power \( P_{hp,i} \) (W). Energy conservation within the heat pump requires \( Q_i' + P_{hp,i} = Q' \). The ratio of \( Q'/P_{hp,i} \) is the coefficient of performance \( COP_i(\cdot) \) of the heat pump, which is defined by \( COP_i = \alpha \eta_i^{-1} \). Here, \( \alpha(\cdot) \) is the performance factor of the heat pump and \( \eta_i(\cdot) \) is the Carnot efficiency defined by \( \eta_i = 1 - T_{ev}/T_{con} \). Here, \( T_{ev}(K) \) and \( T_{con}(K) \) are the evaporation and condensation temperature, respectively, of the heat pump defined by \( T_{ev} = T_i - \Delta T_{hp} - \Delta T_{con} \) and \( T_{con} = T_h + \Delta T_{con} \), where \( \Delta T_{hp}(K) \) is the temperature difference between inflow and outflow of the heat pump on the network side and \( \Delta T_{ev} \) and \( \Delta T_{con} \) are heat exchanger specific temperature differences. For simplification, we set \( \Delta T_{in} = 0 \) and \( \Delta T_{con} \)
= 0. In summary, \( P_{hp,i} \) can be expressed as
\[
P_{hp,i} = \frac{q_i T_h + \Delta T_{hp} - T_i}{T_h}.
\]
The goal is to maximize \( T_i \) to minimize \( P_{hp,i} \). All parameters used in this study are summarized in Table 1.

| Description                                      | Symbol | Unit       | Value |
|--------------------------------------------------|--------|------------|-------|
| Outflow temperature of the source                | \( T_{s,out} \) | °C         | 10, 20, 30 |
| Volume flow through the source                   | \( V'_s \) | m³ h⁻¹     | 3     |
| Heat demand of the loads                         | \( Q'_s \) | kW         | 10    |
| Temperature for heating                          | \( T_s \) | °C         | 35    |
| Temperature difference across heat pump          | \( \Delta T_m \) | °C | 4    |
| Performance factor of heat pump                  | \( \alpha \) |             | 0.5   |
| Specific heat capacity of water                  | \( c_p \) | J kg⁻¹ K⁻¹ | 4178  |
| Density of water                                 | \( \rho \) | kg m⁻³     | 1000  |

Table 1. Boundary conditions for the comparison of the TLTN and the RLTN

3. Electric power consumption of heat pumps
A steady state is reached when the thermal power \( Q'_s \) (W) supplied from the source \( S \) to the network is equal to the thermal power \( Q_{s,out} = \sum Q_{s,i} \)' extracted from the network. Here
\[
Q'_s = c_p q_i V'_s (T_{s,out} - T_{s,in}).
\]

with \( c_p (J \text{ kg}^{-1} \text{ K}^{-1}) \) being the specific heat capacity of water, \( q (\text{kg m}^{-3}) \) being the water density and \( T_{s,in} \) (K) being the inflow temperature to the source (Fig. 1). As all parameters except \( T_{s,in} \) in (1) are constant, \( Q'_s \) depends on \( T_{s,in} \) only. For a qualitative understanding of the steady state, we assume that, initially, the entire network has the temperature \( T_{s,out} \). The circulation pumps are active but the heat pumps are not in operation. In this situation \( T_{s,in} = T_{s,out} \) and \( Q'_s = 0 \). Thereafter, the heat pumps start extracting heat from the network. At first, the temperatures (including \( T_{s,in} \)) in the network only slightly decrease, \( Q'_s \) is still small and \( Q_{s,out} > Q'_s \). Thus, more heat is extracted by the loads than supplied by the source and the entire network continues cooling down. With the network cooling down, \( T_{s,in} \) decreases and consequently \( Q'_s \) increases. This process continues until \( Q_{s,out} = Q'_s \). In this situation, the steady state is reached. For the TLTN, the boundary conditions (Table 1) determine all system parameters for the steady state. For the RLTN, however, the volume flow \( V'_{s,in} \) in the main mesh can be freely chosen. Here, we limit the choice of \( V'_{s,in} \) to \( V'_{s,in} \geq V'_s (i = 1 \text{ to } 4) \) and \( V'_{s,in} \geq V'_s \). This ensures, that the volume flows in the bypasses (Fig. 1b) are at all time in the same direction as \( V'_s \) and that the temperatures supplied to the heat pumps are equal to the network temperatures \( T_s \). Mixing occurs when the return flows of the loads \( V'_s \) and the source \( S \) are reinjected into the network (mixing points in Fig. 1). The steady state is found by a Matlab algorithm that varies \( T_{s,out} \) between -15 °C and 30 °C and searches for the system parameters that hold \( Q_{s,out} = Q'_s \). Table 2 shows the steady state parameters for \( T_{s,out} = 20 \) °C and three network configurations, the TLTN and two RLTNs (RLTN1 and RLTN2) of different \( V'_{s,in} \). In the TLTN, the steady state is only possible for \( V'_{s,in} = 7.24 \text{ m}^3 \text{ h}^{-1} \). In the RLTN1 we chose \( V'_{s,in} = V'_s = 3.00 \text{ m}^3 \text{ h}^{-1} \) corresponding to minimum flow and in RLTN2 we used \( V'_{s,in} = 7.24 \text{ m}^3 \text{ h}^{-1} \) for direct comparison to the TLTN.

We first compare the TLTN to the RLTN1. Because \( V'_{s,in} > V'_s \) in the TLTN, the temperature \( T_i \) supplied to the first heat pump is mixed down to \( T_i = 14.35 \) °C, whereas in RLTN1 with \( V'_{s,in} = V'_{s,out} \) the output temperature of the source \( T_{s,out} = T_i = 20 \) °C is delivered directly to the first heat pump. Because of the larger \( T_i \) in the RLTN1, the heat pump of the load \( L_1 \) reaches a larger \( COP_i = 8.11 \) compared to the TLTN with \( COP_i = 6.25 \). In RLTN1, the temperatures decrease sequentially from load to load. Before load \( L_3 \), the temperature is \( T_i = 17.48 \) °C, before load \( L_3 \) it is \( T_i = 15.01 \) °C, and before load \( L_4 \) it is \( T_i = 12.56 \) °C and correspondingly \( COP_i = 7.16 \), \( COP_i = 6.42 \) and \( COP_i = 5.83 \). In the TLTN, all loads receive the same temperature of 14.35 °C corresponding to a \( COP = 6.25 \). Because the mean \( COP = 6.88 \) of the heat pumps in RLTN1 is larger than the mean \( COP = 6.25 \) in the TLTN, the total electricity consumption of the heat pumps \( P_{hp} = 5.90 \text{ kW} \) in the RLTN1 is smaller than the total electricity consumption \( P_{hp} = 6.40 \text{ kW} \) in the TLTN, here by 8 %. If the volume flow in the main mesh of the
RLTN is kept equal to the volume flow in the TLTN, the electricity consumption of the heat pumps in the RLTN is 6 % larger than in the TLTN (column RLTN2 in Table 2). Figures 2a shows the mean COP and Figure 2b the ratio of the electricity consumption of the heat pumps in the RLTN and the TLTN in dependence of $V_m'$ for three different source temperatures $T_{s,out} = 10 \, ^\circ C$ (blue), $20 \, ^\circ C$ (green) and $30 \, ^\circ C$ (red). The three green circles in Figures 2a, b indicate the discussed situations above. Figures 2a, b show that for all $T_{s,out}$ and small $V_m'$ the RLTN performs better than the TLTN but worse for large $V_m'$. The larger $T_{s,out}$, the stronger does the performance depend on $V_m'$. For $T_{s,out} = 10 \, ^\circ C$ the maximum benefit of the RLTN is 4 %, for $T_{s,out} = 20 \, ^\circ C$ it is 8 % (as discussed above) and for $T_{s,out} = 30 \, ^\circ C$, it is 15 %.

![Table 2. Steady state results of the TLTN and the RLTN. Boundary conditions are shaded and main evaluation parameters for the comparison are in bold.](image)

### 4. Hydraulic power losses in the main mesh

The hydraulic power $P_{\text{hyd},m}$ (W) provided by the circulation pumps in a hydraulic system can be expressed by $P_{\text{hyd},m} = \sum_i P_{\text{hyd},i} = \sum_i \Delta p_i V_i'$, where index $i$ corresponds to network section $i$ and the sum over $i$ includes all network sections in the system. For each network section, $P_{\text{hyd},i}$ (W) is the hydraulic power loss, $\Delta p_i$ (Pa) the pressure loss and $V_i'$ (m$^3$ s$^{-1}$) the volume flow in section $i$. Here, we focus on the hydraulic power losses in the main mesh only and neglect the loads. Whereas the volume flow in the main mesh is constant in the RLTN, it decreases from load to load with increasing distance from the main pump in the TLTN. For the comparison, we divide the main mesh with $N$ loads in $N$ equally long pipe sections with the same hydraulic resistance $C$ (Pa s$^2$ m$^{-1}$). The hydraulic power loss in the main mesh is then

$$P_{\text{hyd},m} = \sum_{i=1}^{N} \Delta p_i V_i' = C \sum_{i=1}^{N} V_i'^{3/2}$$

Here, we used the quadratic dependence of the pressure loss on the volume flow $\Delta p_i = CV_i'^{2}$. In the RLTN, $V_i' = V_m'$ and thus

$$P_{\text{hyd},m,RLTN} = CV_m'^{3/2}N$$

For four clients, $N = 4$ and $P_{\text{hyd},m,RLTN} = 4CV_m'^{3}$. In the TLTN, $V_i'$ decreases by $(1/N)V_m'$ after each load. Therefore,
$P_{hyd,m,TLTN} = C \sum_{i=1}^{N} \left( \frac{i}{N} V_m' \right)^3 = CV_m' \sum_{i=1}^{N} \left( \frac{i}{N} \right)^3$ 

For $N = 4$, $P_{hyd,m,TLTN} = 1.56 CV_m'^3$. For equal $V_m'$ in the RLTN and the TLTN, the ratio of the hydraulic losses in the main mesh is 

$$P_{hyd,m,rat} = \frac{P_{hyd,m,RLTN}}{P_{hyd,m,TLTN}} = \frac{N \sum_{i=1}^{N} \left( \frac{i}{N} \right)^3}{\sum_{i=1}^{N} \left( \frac{i}{N} \right)^3}$$  \hspace{1cm} (2)$$

For $N = 4$, this ratio is 2.56. Interestingly, for $N \rightarrow \infty$, $P_{hyd,m,rat}$ converges to 4. However, as the volume flow in the main mesh of the RLTN is adjustable, $P_{hyd,m,RLTN}$ can be reduced. In the RLTN1, the hydraulic power losses are 82% less compared to the TLTN (Table 2). In the RLTN2 with equal volume flow $V_m'$ as in the TLTN the hydraulic losses in the main mesh are by a factor of 2.56 larger than in the TLTN. Figure 2c shows the ratio of the hydraulic power losses of the RLTN and the TLTN for the three different source temperatures. In all cases, the volume flow $V_m'$ has large influence on the hydraulic losses in the main mesh.

**Figure 2.** Results of the comparison of the RLTN to the TLTN topology in dependence of the volume flow $V_m'$ in the main mesh for three different source temperatures. a, Coefficient of performance COP, b, Electric power consumption of the heat pumps in the RLTN and the TLTN normalized by the electric power consumption in the TLTN. c, Hydraulic power losses in the main mesh of the TLTN and the RLTN normalized by the hydraulic power losses in the TLTN. The vertical dashed line indicates the minimum flow of $V_m' = V_{S,out}' = 3 \text{ m}^3 \text{ h}^{-1}$. The horizontal dashed line in (c) indicates the ratio of 2.56 for $N = 4$ in equation (2) and for equal volume flows in the TLTN and the RLTN. The three green circles in (a,b) represent the three cases of the three columns in Table 2.

5. **Discussion and future work**

The main limitation of the work is the simplified network design. For example, the equal heating demand of the four loads allows for a large reduction of $V_m'$ in favor of the RLTN. The situation may be different if loads of varying heating and cooling demands were taken into account.
Moreover, the source produces a constant outflow temperature $T_{s,\text{out}}$. In reality, the outflow temperature is a function of the inflow temperature $T_{s,\text{in}} = T_s$. The additional dynamics resulting from the feedback of $T_{s,\text{in}}$ on $T_{s,\text{out}}$ were not considered in the comparison and may affect the results.

The hydraulic comparison was extremely simplified. It neglected hydraulic power losses in the loads and assumed constant pipe diameters in the main mesh of the TLTN. We expect that the “valve-free” RLTN has less hydraulic power losses in the loads and that the comparison will change in favor of the RLTN when pressure losses in the loads are included in the comparison.

Future comparisons will thus be based on realistic dynamic heating and cooling demands, realistic feedback mechanisms in the source and a complete comparison of the electricity consumption of the circulation pumps. As robustness, flexibility, and investment costs are important criteria for the choice of a topology, future work will also include operation suggestions and an estimate of investment costs.

6. Conclusion

The serial arrangement of heat pumps is often considered to have a negative effect on the COP, as the heat pumps further away from the source receive colder input temperatures. In this work, we showed that heat pumps that are connected in series in the reservoir low-temperature network can consume, in total, less electricity than the heat pumps that are connected in parallel in traditional low-temperature networks, in particular for high source temperatures. However, this is only the case, if the volume flow in the main mesh of the RLTN is kept small. At small volume flows in the main mesh, also the hydraulic power losses in the RLTN are smaller than in the TLTN. At large volume flows in the main mesh, however, the RLTN topology is less efficient than the TLTN topology, both in terms of electricity consumption of the heat pumps and hydraulic losses in the main mesh.

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