NON-LINEAR THERMAL NETWORKS – HOW CAN A MESHED NETWORK IMPROVE ENERGY EFFICIENCY?

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ABSTRACT

A promising mean to realize the integration of decentralized thermal energy sources in districts and urban areas are low-temperature-networks (LTN). However, the general modus operandi of LTN can differ greatly. A very common approach in district heating is to supply consumers with heating and cooling power on the bases of unidirectional mass and energy flows. These systems consist of supply and return ducts. On the other hand, more recently designed networks operate on bidirectional mass and energy flows between a warm and cold duct. The underlying concept is inherently non-linear in character and still bears some challenges and open questions to research.

The question addressed here is what conceptual system design is more energy efficient. With reference to already realized systems, namely “ETH Hönggerberg” and “Brig-Naters”, two simulation models were developed and equally parametrised to compare their conceptual designs in regard to their exergetic efficiency. One system operates on unidirectional, the other on bidirectional mass and energy flows. The simulation models consider consumers with heating and cooling demands and a source. For both systems the energy and exergy flows as well as the auxiliary powers were calculated.

Keywords: low-temperature networks, energy efficiency, exergy analysis, modelling, simulation

INTRODUCTION

Low-temperature networks (LTN) are characterized by their reduced operating temperature of approximately 8°C – 20°C. At this temperature level energy transportation losses are significantly reduced and by far less an issue when compared to district heating and cooling networks, which are operating at higher (or lower) temperature levels. A further benefit of LTN is the possibility of freecooling, which is especially advantageous when a seasonal storage is implemented within the LTN. However, these benefits are accompanied with the necessity of heat pumps that provide a sufficient temperature level. The heat pump’s efficiency directly depends on the temperature spread and it follows that the building standard of the LTNs customers is a crucial factor. But in the case of a well-defined surrounding, how important is the modus operandi of thermal networks itself?

To approach this question, we compared two different conceptual designs of thermal networks. Each of them comprised the same heating unit (H) drawing heat from the system, the same cooling unit (C) feeding heat into the system and an ideal source, which heats up the system, respectively cools it down if necessary according to simple control regulatories. The first type of system refers to the thermal network of “Brig-Naters” and operates on unidirectional mass and energy flows and is equipped with a centralized circulation pump. The network’s source keeps the temperature of the supply duct within a certain bandwidth. The second system refers to the thermal network of “ETH Hönggerberg” that consists of a warm and a cold duct having circulation pumps located at each costumer of the LTN. In contrast to the unidirectional approach, each costumer conveys the amount of water bidirectional for himself, i.e. from whatever duct that fits his temperature demand best. In a first step focus was set on the annual operational performance of each system. Therefore the heat flux and exergy flow were quantified and all exergy flows across the LTN systems were calculated.

METHOD

The two thermal networks were built-up using in-house developed simulation modules, which are described in [1, 2]. Input data are heat flux profiles for each consumer as shown in Figure 1 and the annual curve of the ambient temperature (not shown here). The heating input profile corresponds to the room heating demand of a greater domestic building with floor heating. On the consumers' side a mean temperature of~35°C was assumed. The cooling demand profile refers to a modern office building using cooling ceilings with an assumed mean temperature of~15°C (freecooling). Each unit draws heat form the LTN with a fixed temperature spread of 4 K. Domestic hot water was not considered in these simulations as it is roughly constant throughout the year and thus only results in an offset.

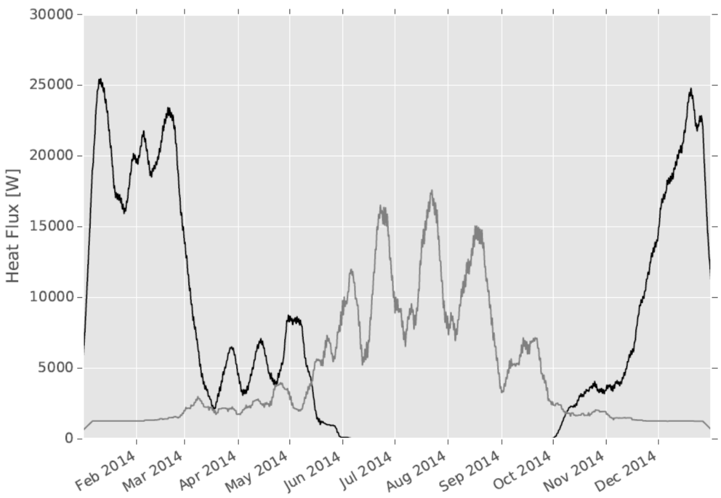

Figure 1: Input data for the simulations. Data frequency is "hour". The profiles were smoothed by a simple moving average (N = 250). The black line is the heat flux demand for heating of a residential building (60 MJ/a). The grey continuous line shows the cooling demand of an office building (40 MJ/a). The overlap of the profiles is 9.8 MJ/a in total.

Figure 2 represents the unidirectional system, which is temperature controlled and driven by the centralized circulation pump. The bidirectional system shown in Figure 3 is more self-regulated in the sense that the consumers' total conveyed mass flows drive the system [1, 2].

The models contain each one cooling unit and one heating unit. To allow for a comparison of both thermal networks, the systems were identically parameterised and kept as simple as possible. Heat fluxes into the LTN are considered positive and negative when leaving the system. The heat pumps were idealized and considered with their highest theoretical efficiency; all heat exchangers were taken into account without losses. Based on the heat fluxes crossing the systems' borders the exergy flows were calculated with reference to the ambient temperature [3]:

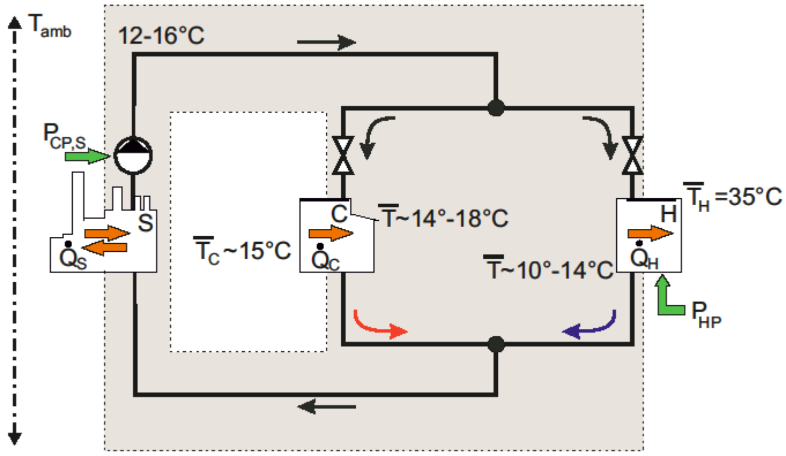

Figure 2: Synoptic presentation of the considered unidirectional thermal network. Mass flow passes the source in one direction. The supply line's temperature is kept in a band of 12-16°C. The coloured background represents the system and its boundaries. Heat and exergy flows cross the system at the source, the cooling and the heating unit. The consumers must throttle down the overall system pressure to achieve the demanded mass flow.

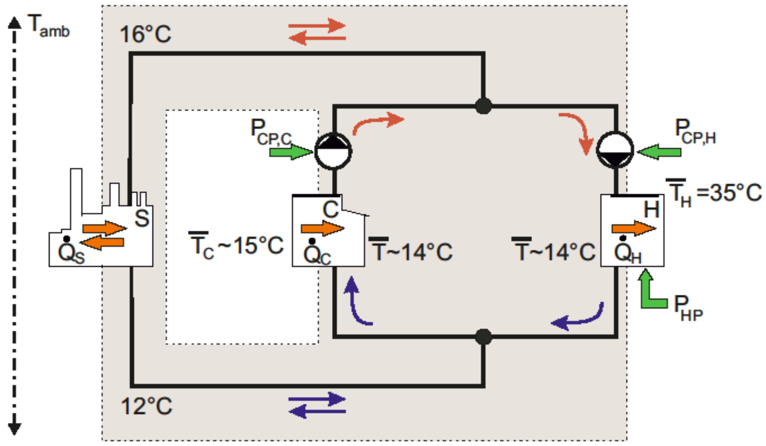

Figure 3: Synoptic presentation of the considered bidirectional thermal network. Mass flow passes the source in both directions. Warm and cold ducts are kept at 16°C/12°C. Each consumer conveys the necessary mass flow from the duct suiting its demand.
(S: Source, C: Cooling unit, H: Heating unit, P_{HP}: Power uptake heat pump, P_{CP}: Power uptake circulation pumps, T_{amb}: ambient temperature, T_C: mean cooling temperature consumer side, T_H: mean heating temperature consumer side)

$$\dot{E} = \left(1 - \frac{T_{amb}}{\overline{T}}\right) \dot{Q}, \quad \text{with } \overline{T} = \frac{T_{in} - T_{out}}{\ln\left(T_{in}/T_{out}\right)}. \tag{1}$$

Temperatures	Source	Heating	Cooling
(T_{in} / T_{out}) – unidir	(T_{supply} / T_{return})	($T_{mean,LTN}$ / $T_{mean,heating}$)	($T_{mean,LTN}$ / $T_{mean,cooling}$)
(T_{in} / T_{out}) – bidir	(T_{warm} / T_{cold}), (T_{cold} / T_{warm})	($T_{mean,LTN}$ / $T_{mean,heating}$)	($T_{mean,LTN}$ / $T_{mean,cooling}$)

Table 1: Different temperature pairs used to calculate the exergy flows

Table 1 gives the temperature pairs used to determine all considered exergy flows. The listed mean temperatures were aggregated values from typical supply and return temperatures at the respective unit and kept constant during the simulations. The used ambient temperature was

the outdoor air temperature, which alike all further network temperatures was variable.
In addition, all auxiliary powers of the heat and circulation pumps were determined as well.

RESULTS

Major simulation results are presented in Figure 4 – 6.

Figure 4 shows the heat fluxes crossing over the source (S) and the belonging thermal exergy flows. 55 MJ/h (unidirectional LTN), respectively 56 MJ/h (bidirectional LTN) of the total necessary 60 MJ/a of heat are delivered from the thermal networks. About 84% of these (55 MJ/a / 56 MJ/a) are fed into the system by the source. The total amount of energy fed into, respectively taken out of the systems differs by 5%, at which the bidirectional system shows the higher total energy flow. It also shows the higher exergetic intake: The unidirectional network yields 60% of the exergy uptake compared to the bidirectional system (annual total energy was normalised for comparison).

Figure 5 gives the exergy flows into the heating unit (H), i.e. the exergy used up by the consumer for its heating purposes. As the consumers in both models are identically, their needs for exergy is identical as can be seen in subplot#3. About 10% of the annual heat consumed is exergy (6 MJ/a) of which in the unidirectional system 76% must be provided by the heat pump and only 65% in the bidirectional system. This reflects in the exergetic efficiency (η_{ex} = $\dot{E}_{H,LTN}$ / P_{WP}). The bidirectional system yields a mean annual exergetic efficiency of ~ 40%, while the unidirectional system only reaches 24%. Thereby the bidirectional system saves about 0.7 MJ/a of electrical energy when directly compared to the unidirectional system.

A similar result was found for the circulation pumps when only ~ 40% of electricity was needed for the circulation pumps in the bidirectional LTN. However, this auxiliary energy was rather minor in magnitude and range from 29 kJ/a to 78 kJ/a, which is partially due to the fact that during the parametrisation of the model other aspects were more focused on.

Figure 6 shows the exergy flows that accompany the heat fluxes during freecooling (C). The figure gives the exergy flows in regard to the consumer and the network, whereas the leading sign was always chosen in reference to the network (positive sign towards, negative sign from the network away). However, a direct comparison of the systems exergy fluxes is in this case not possible. During the framed period (March - November) the mean temperature of the unidirectional system (~ 23°C) is higher than the temperatures necessary for freecooling (~ 15°C) and thereby not available.

DISCUSSION

In Figure 1 the overlap of the two input profiles is about 17%, i.e. ideally only 84% of energy must be fed into the system by the source from outside. The simulations showed such an ideal reuse of the available waste heat coming from the cooling unit. This is due to the fact that thermal losses of the pipes, losses of the heat exchanger and heat pumps were neglected and the components idealized. But this also gives a first albeit simple validation of this approach.
The finding in subplot#3 of Figure 5 is another indication as it shows that the additional amount of exergy flow gained in the bidirectional thermal network is equal to the additional power uptake of the heat pumps in the unidirectional system. Thus it becomes obvious that the choice and design of the system has a profound influence on the exergy efficiency and can be estimated with the help of simulations. A further important aspect besides the principle design of a system is how the system is operated on. The results in Figure 6 are an example how specification of the source turns freecooling for a long period of the year into unwanted

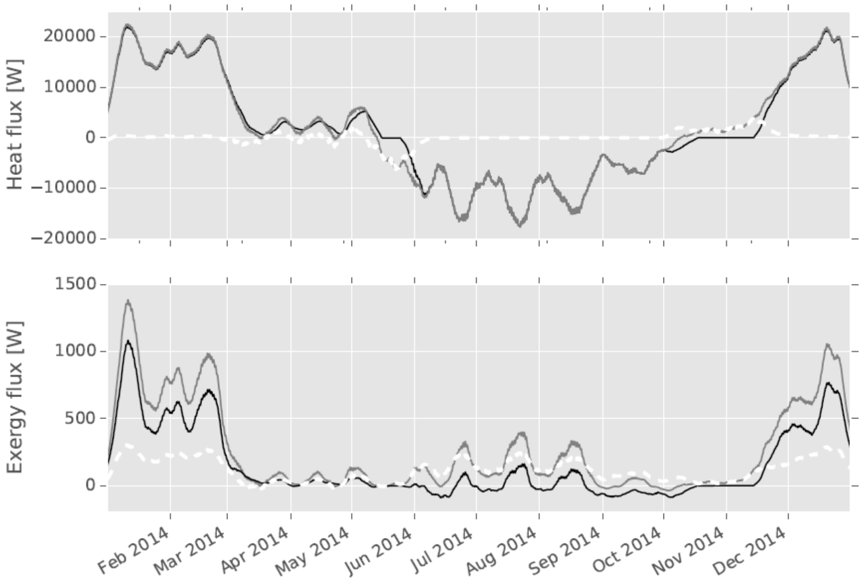

Figure 4: Heat flux (subplot#1) and exergy flows through the source (positive: into, negative: out of system). In black the results for the unidirectional, in grey for the bidirectional system. The difference is shown in white (dashed) line.

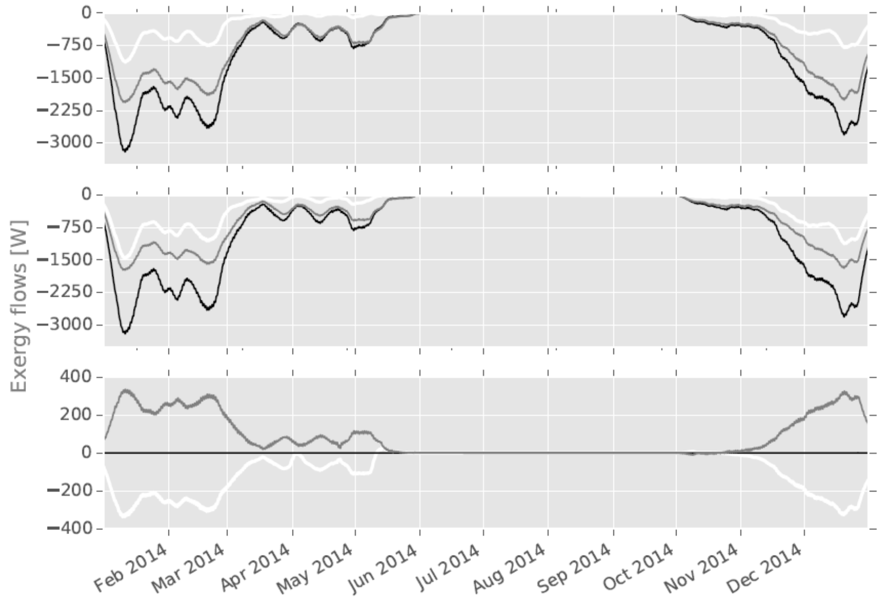

Figure 5: Exergy flows into the heating unit. Subplot#1 describes the unidirectional system; subplot#2 the bidirectional system; subplot#3 the difference subplot#1 – #2. The necessary total exergy flow for heating (black) is equal in both network typologies. Thermal exergy flows from the LTN are depicted in white and the exergy rose by the heat pump in grey.

"free-heating". This result does not affect the simulation by itself at large, because the exergetic calculations were done in a post-processing process and as long as it is presumed that the heat is fed into the system by an alternative (mechanical) cooling process. A further aspect of Figure 6 is the inherent loss of exergy alone due to the different mean temperatures of the LTN and consumer, which offers another chance for optimisations and the study of interfaces.

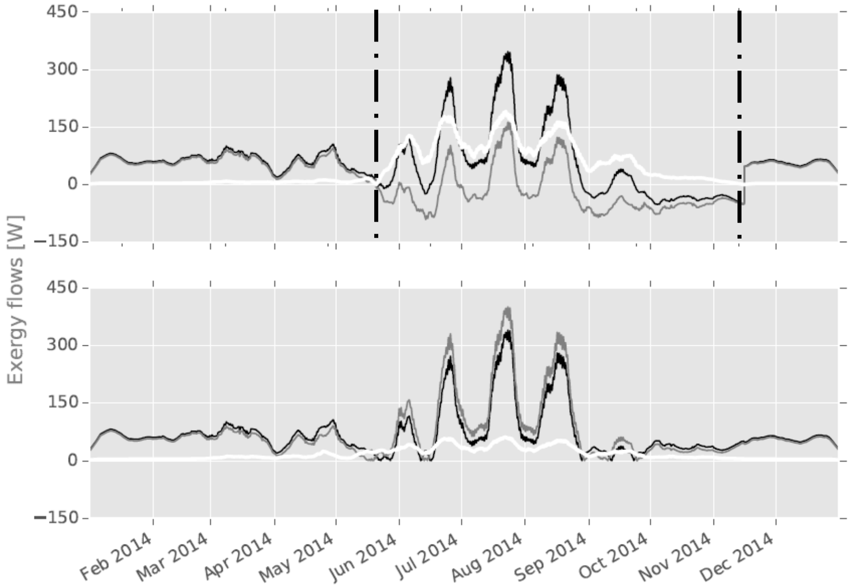

Figure 6: Exergy flows in the cooling unit. Subplot #1 shows the results for the unidirectional system, subplot #2 for the bidirectional. In black the exergy flow from the consumer is shown, in grey the exergy flow to the LTN. The white dashed line is the absolute loss of exergy due to different mean temperatures. The period framed by the dashed lines is explained in the text.

CONCLUSION

In this study two simulation models of LTN with different modus operandi were compared. The first system relies on the regulation of temperature and unidirectional mass flow, while the second allows bidirectional mass flows, but keeps two separate temperature levels. For equal parametrisation the simulation showed a clear advantage of the LTN operating with separate temperature levels and bidirectional mass flows. It outperforms the other in terms of exergetic receptiveness and economy and clearly allows the saving of electricity of significant magnitude.

To improve the model and to provide a tool for the conceptual design process some extensions should be thought of. Among others a more detailed model to describe the interplay of the LTNs and the consumers' temperatures would be certainly of great benefit. But equally important is a systematic sensitivity analysis to gain a better understanding of both system and to allow for a more balanced assessment, which then finally could result in recommendations of best practice.

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