An exergy-based district heating modeling for optimal thermo-hydraulic flow distribution: application to BlueFactory's Smart Living Lab neighbourhood

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Abstract:
Low temperature district heating networks can provide a highly efficient low carbon heat supplier with great potential in improving heat distribution while minimizing exergy losses. However the interest in performing exergy analysis is hardly comprehensive for industry as it rarely gives explicit details on district heating systems design and operation. Moreover, most of exergy assessments are based on the assumption of neglecting pressure losses whereas low temperature district heating networks usually operate at low differential temperature corresponding to high flow rates and then significant pressure losses. Consequently, the latter are no longer negligible when compared to thermal losses. An exergy formulation as function of thermal and pressure losses is therefore essential to assess low temperature DH networks.
This paper presents an exergy-based methodology to design low temperature networks for an optimal thermo-hydraulic flow distribution. It addresses an explicit analytic expression of exergy losses as a function of geometric and thermo-hydraulic parameters. A detailed exergy model is performed to identify influencing parameters and conclude on a simplified formulation of exergy losses. The method is tested on the conception of the evolving thermal network for the BlueFactory site in Fribourg (Switzerland) composed of 11 buildings with a total surface area of $74500\ m^2$.

Keywords:
Low District Heating Networks, Thermodynamics, Energy, Exergy, Sustainability.

1. Introduction

In a context of densification and concentration of the population in urban areas, Seto et al. [1] estimates that cities contribute to more than 70% of global energy use and up to 50% of global greenhouse gas emissions. Heating and cooling account for half of the total consumption of buildings as mentionned by the International Energy Agency [2]. Traditional conversion systems for heating and cooling production (boilers, chillers, heat-force coupling systems) need to be re-thought for the integration of efficient thermal systems using renewable energy sources. Talebi et al. [3] highlighted that thermal networks represent an interesting alternative insofar as they fit into the concept of multi-energy systems, aggregators of diversified energy sources and therefore empowering local communities and prosumers. Their performances are influenced by several variables, which, besides counting for a significant portion of annual operation costs due to heat losses, have a non-negligible environmental impact as shown by Li et al. [4]. Thermal capacity being a function of water flow rate and temperature differentials (difference between supply and return temperature at the substation), the distribution piping system is at the heart of stakes for industries:

- for a constant pressure gradient, increasing temperature differentials reduces pipes diameters and therefore the capital investments
- reduced flow rates decreases pumping requirements

- pipe diameters dimensions depend on the maximum allowable flow velocity
- controlling the differential pressure contributes in achieving low return temperatures implied by an accurate distribution of water flow rate in the supply network as shown by Thorsen and Boysen [5]

Those points emphasize the need to think no longer in terms of energy quantity but energy quality. Indeed, as heat demand in buildings is getting lower, so are temperature differentials which reduces significantly the exergy efficiency in substations. According to Li and Svendsen [6] and Castro Flores et al. [7], the largest relative exergy losses are caused by heat losses in the distribution network and domestic hot water, space heating production in substations leading to exergy destruction mainly during high heating load seasons. It also strengthens the relevance of an exergy analysis by comparing the thermal bypass influence on energy and exergy efficiency, which is respectively 85% to 42% due to exergy loss caused by bypass water mixing. In fact, Tsatsaronis points out [8] that as "exergy analysis identifies the location, the magnitude and the sources of thermodynamic inefficiencies in a system", it is therefore a powerful tool to asses thermal networks' perfomances with benefits over their entire life cycle. This is shown by Dagmar Kallert [9] who developed a holistic exergy-based assessment method to compare different strategies for low district heating networks or with Ljubenko's et al. [10] exergy-based methodology to analyse a distribution network leading to recommendations for higher exergy efficiencies of heat supply to different points in the network. Nevertheless, most of exergy assessments are based on the assumption of neglecting pressure losses whereas low temperature district heating networks usually operate at low differential temperatures corresponding to high flow rates and significant pressure losses. Consequently, the latter are no longer negligible when compared to thermal losses. Moreover, industries and engineers could ask the justified question raised by Tsatsaronis [8] "And now that I know how much exergy is destroyed in each component of a system what do I do?". Reasons explaining the low use of exergy both economically and politically are not only to be found in the abstraction of the concept but also as it rarely gives explicit details on thermal networks' design and operation. Many research projects use the concept of exergy for system analysis in various fields, but no explicit formulation currently exists for thermal networks. An exergy formulation as function of thermal and pressure losses is therefore essential to assess low temperature district heating networks. The scientific contribution of this paper is to determine an exergy-based methodology to model thermal networks for an optimal flow distribution by addressing an explicit analytic expression of exergy losses as a function of geometric and thermo-hydraulic parameters.

2. Exergy approach for Low temperature district heating Networks (LowNeX)

According to Tsatsaronis [8], the exergy of a thermodynamic system (or stream) is defined as the maximum theoretical useful work (shaft work or electrical work) obtainable as the system (or stream) is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system (or stream) interacts with this environment only. Therefore, the exergy potential of a given flow depends on several factors, including the temperature level and the system environment. These determine the amount of internal energy released by the system to reach thermodynamic equilibrium with its environment. In this study, low-temperature networks are considered to be low-pressure networks, like in the industry, thus limiting the pressure to 5 bars and the plant supply temperature to $110\ ^{\circ}C$ as shown in Fig. 1.

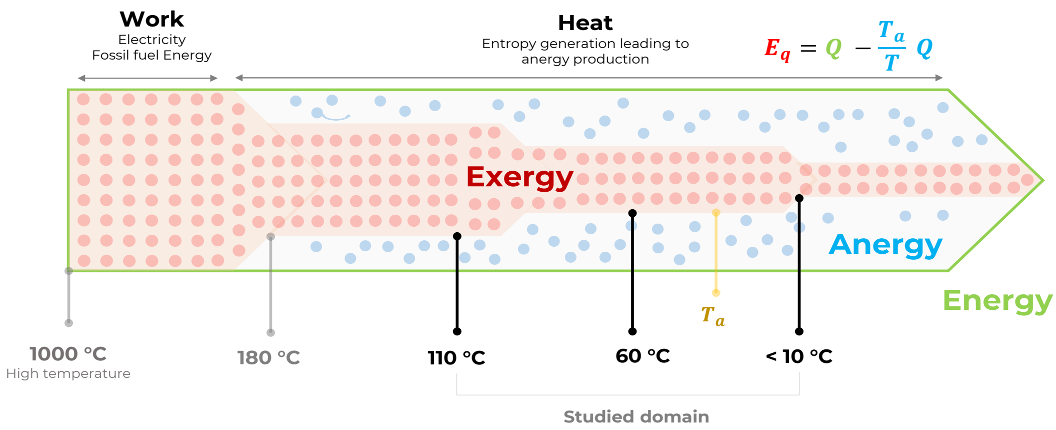

Figure 1: Illustration of district heating networks' exergy efficiency for the considered temperature range in LowNeX project

The exergy balance formulation used in this paper is in accordance with Borel and Favrat [11] by introducing $\dot{\mathbf{E}}_\mathbf{q}$, the exergy balance relating to heat transfer, $\dot{\mathbf{E}}_\mathbf{m}$, the exergy balance relating to mass transfer (and therefore to an open system), $\dot{\mathbf{E}}_\mathbf{w}$, the exergy balance relating to an exchange of work.

$$\underbrace{\frac{dE_u}{dt}}_{\text{exergy variation rate}} = \dot{\mathbf{E}}_\mathbf{q} + \dot{\mathbf{E}}_\mathbf{m} + \dot{\mathbf{E}}_\mathbf{w} - \underbrace{T_a \frac{\delta S^i}{dt}}_{\text{system exergy losses, } \dot{L}} \tag{1}$$

Thereafter, the exergy losses are represented by the positive quantity $\dot{L}$. Variables noted in bold are algebraic: they can be positive (received by the system) or negative (given out).

3. Exergy-based district heating modeling

In order to establish a generic expression of exergy losses suitable to any network, the system bound by the dotted lines in Fig. 2 is considered. The thermal network is considered as an open thermodynamic system, without exchange of work but exchanging heat with a cold source (consumer) and a hot source (power plant). The exergy balance relating to mass transfer $\dot{\mathbf{E}}_\mathbf{m}$ is expressed as the difference between the mass exergy supplied by the power plant $\dot{E}_{m,s}$ and the one given by the system to the user $\dot{E}_{m,f}$:

$$\dot{\mathbf{E}}_\mathbf{m} = \dot{E}_{m,s} - \dot{E}_{m,f} \tag{2}$$

$$\dot{E}_{m,s} = \dot{M}(\underline{\Delta} h_s - T_a \underline{\Delta} s_s) \tag{3}$$

$$\dot{E}_{m,f} = \dot{M}(\underline{\Delta} h_f + T_a \Delta s_f) \tag{4}$$

with $\underline{\Delta} h_s = h_s - h_{s'}$, $\underline{\Delta} h_f = h_f - h_{f'}$, $\underline{\Delta} s_s = s_s - s_{s'}$ et $\Delta s_f = s_{f'} - s_f$. The operator $\underline{\Delta}$ defines a difference between an initial and a final state, as opposed to the operator Δ.

The boundary chosen is outside the system, where the temperature corresponds to the ambient temperature T_a. Exergy losses of the system are then expressed as follows:

$$\dot{L} = \dot{M}\left[(\underline{\Delta} h_s - \underline{\Delta} h_f) - T_a(\underline{\Delta} s_s + \Delta s_f)\right] \tag{5}$$

Without neglecting pressure losses, the enthalpy and entropy variations of an incompressible liquid can be expressed as follows:

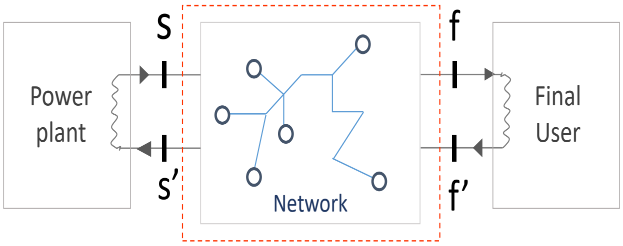

Figure 2: Considered thermodynamic system delimited by the dotted lines

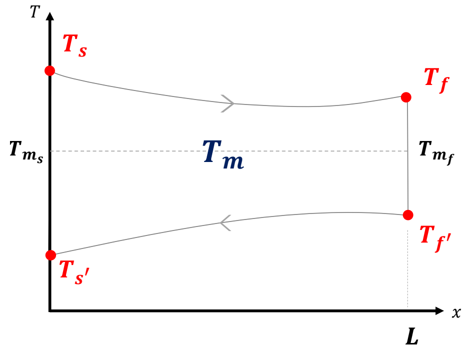

Figure 3: Diagram of temperature evolution in the system

$$dh = c_p dT + v dP \tag{6}$$

$$ds = c_p \frac{dT}{T} - \frac{v}{T}\, dP \tag{7}$$

By introducing and integrating the pressures at each point, the following relationships are obtained:

$$\underline{\Delta} h_s = c_p\, \underline{\Delta} T_s + \overline{v} \underline{\Delta} P_s \tag{8}$$

$$\underline{\Delta} h_f = c_p\, \underline{\Delta} T_f + \overline{v} \underline{\Delta} P_f \tag{9}$$

Furthermore, the specific volume at constant pressure is approximated by the ratio of the average specific volume and exchange temperature ($\frac{v}{T} \backsimeq \frac{\bar{v}}{T_{m,exchange}}$ et $v = \bar{v} = constant$). Entropy differentials are expressed as follows:

$$\underline{\Delta} s_s = c_p \ln \frac{T_s}{T_{s'}} - \frac{\overline{v}}{T_{m,s}} \underline{\Delta} P_s \tag{10}$$

$$\Delta s_f = c_p \ln \frac{T_{f'}}{T_f} - \frac{\overline{v}}{T_{m,f}} \Delta P_f \tag{11}$$

where $T_{m,s}$ and $T_{m,f}$ denote the average temperatures between the inputs and outputs on the user side and on the power plant side. Fig. 3 allows to visualize the temperature evolution of the considered system. The average temperature of the entire network, denoted as T_m, is defined by stating that:

$$T_{m,s} = \frac{T_s + T_{s'}}{2} \backsimeq T_m \tag{12}$$

$$T_{m,f} = \frac{T_f + T_{f'}}{2} \backsimeq T_m \tag{13}$$

Equation (5) becomes:

$$\dot{L} = \dot{M} c_p \left[(\underline{\Delta} T_s - \underline{\Delta} T_f) - T_a \ln(\frac{T_s\, T_{f'}}{T_f\, T_{s'}}) + (1 + \frac{T_a}{T_m})\, \frac{\overline{v}}{c_p} (\underline{\Delta} P_s + \Delta P_f) \right] \tag{14}$$

By setting $\Delta T_{tot} = \underline{\Delta} T_s - \underline{\Delta} T_f$, the temperature drop of the network, and $\Delta P_{tot} = \underline{\Delta} P_s + \Delta P_f$, the global pressure drops of the network (excluding substations and generating station), (14) becomes:

$$\dot{L} = \underbrace{\dot{M}c_p[\Delta T_{tot} - T_a \ln(\frac{T_s\, T_{f'}}{T_f\, T_{s'}})]}_{\text{Thermal exergy losses}} + \underbrace{\dot{M}(1 + \frac{T_a}{T_m})\, \bar{v}\, \Delta P_{tot}}_{\text{Viscous dissipation exergy losses}} \tag{15}$$

This generic formulation of the exergy losses gives an explicit equation to optimize networks' geometrical and thermal parameters. It involves the average temperature of the network as well as the temperature levels on the power plant and substation sides. Two components are to be distinguished: thermal exergy losses (which group together the temperatures on the network) and exergy losses by viscous dissipation (depending on pressure drops).

3.1. Modeling approach

The following section presents the thermal and hydraulic models used to assess (15). A **segment** is defined as the combination of a supply pipe and a return pipe having the same physical properties (length, diameter, roughness, exchange coefficient...) and delimited by the same inlet and outlet points.

3.1.1. Thermal pipe modeling

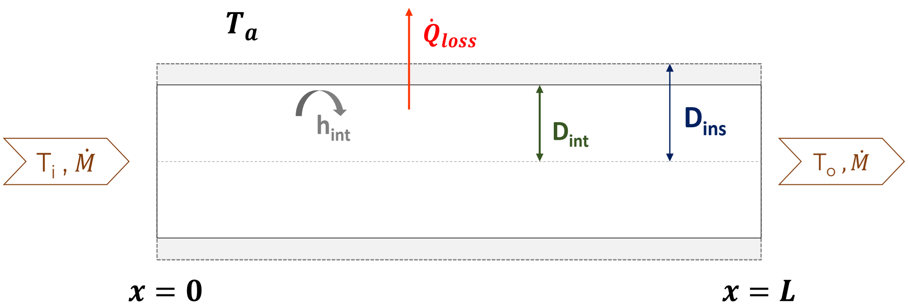

Figure 4: Thermodynamic flow representation of a pipe in a segment

The temperature variation in an insulated segment of pipe is considered to be one-dimensional along the x-axis. With $T_{m,p} = (T_i + T_o)/2$ denoted by the average temperature on the pipe segment, the energy conservation equation gives the pipe outlet temperature T_o:

$$\dot{Q}_{loss} = UL(T_{m,p} - T_a) \tag{16}$$

$$T_o = \frac{T_i(\dot{M}c_p - \frac{UL}{2}) + ULT_a}{\frac{UL}{2} + \dot{M}c_p} \tag{17}$$

The particular case of buried pipes is considered. Thus, by neglecting the strength of steel pipes and assuming conduction in the ground up to a distance H where $T = T_a$, the overall heat transfer coefficient U is deducted.

$$U = \left[\frac{1}{\pi D_{ins} h_{int}} + \frac{\ln(\frac{D_{ins}}{D_{int}})}{2\pi\lambda_{ins}} + \frac{\ln(\frac{H}{D_{ins}})}{2\pi\lambda_g}\right]^{-1} \qquad [\mathrm{W/(mK)}] \tag{18}$$

The insulation diameter D_{ins} is equal to twice the internal diameter of the pipe and h_{int} to the internal exchange coefficient of the pipes.

3.1.2. Hydraulic pipe modeling

The viscosity of the fluid causes viscous friction and generates exergy dissipation. Linear and singular pressure drops, denoted ΔP_{lin} and ΔP_{sin}, over the pipe segment of length L are expressed by:

$$\Delta P_{lin} = \frac{8\Lambda L\rho\dot{V}^2}{D_{int}^5\pi^2} \tag{19}$$

$$\Delta P_{sin} = \sum_k \frac{8\rho\dot{V}^2}{D_{k,int}^4\pi^2}\xi_k \tag{20}$$

The friction factor Λ is calculated with Churchill's expression [14]. As a first approach, only one bend per meter of pipe is integrated in the model ($\xi_k = 0.2L$) and singular pressure drops account for 5% of total pressure drops.

4. Parametric study and discussion

Since the main concern of network planners is to minimize losses while meeting consumer demand, it is essential to set geometric and operational parameters (length, diameter, temperature of the network, etc.) in order to maximize the efficiency of the network throughout the year. This section examines the influence of design and operating parameters on exergy losses using the formulation expressed by (15). The constant values of the problem are presented in Table 1.

k, mm	$T_a, °\text{C}$	λ_g	$\lambda_{ins}, W/(mK)$	$c_p, J/(kgK)$	$\rho, kg/m^3$	$\nu, m^2/s$
45	0	1.2	0.2	4195	997	$4.74\ 10^{-7}$

Table 1: Constant values of the problem

4.1. Influence of design parameters

Five network case studies with different nominal powers are considered, having as common characteristics a total length of $1000\ m$, a supply temperature of $70°C$ and a temperature drop at the final user (temperature differential ΔT_f) of $21°C$.

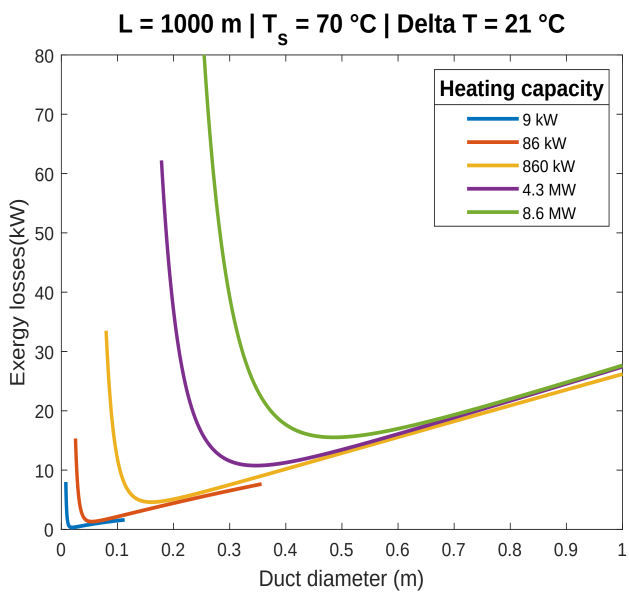

Figure 5: Variation of exergy losses versus average pipe diameter set by nominal network capacities

Depending on the nominal capacity, an optimal diameter minimizing the total exergy losses exists. In fact, Fig. 5 represents, for these 5 networks, the evolution of exergy losses as a function of the average pipe diameter. It shows that the optimum diameter, specific to each network, increases with the capacity from $160\ mm$ for a $860\ kW$ network to $330\ mm$ for a $4\ MW$ network. The source of this optimum can be explained by the exponential increase of exergy losses by viscous dissipation with fluid velocity (thus the small diameters because the power and the temperature differential are fixed) in parallel with the decrease of thermal exergy losses.

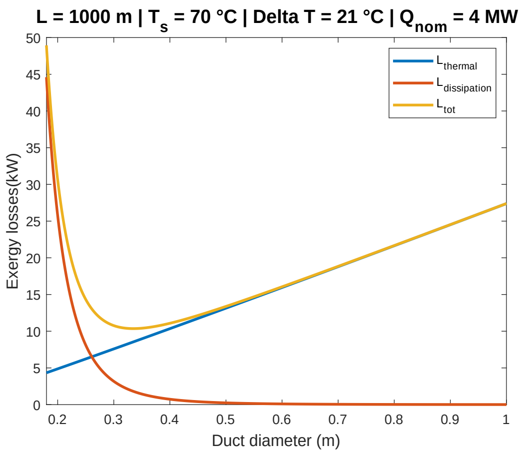

Figure 6: Distribution of exergy losses versus diameter for a design capacity of 4 MW

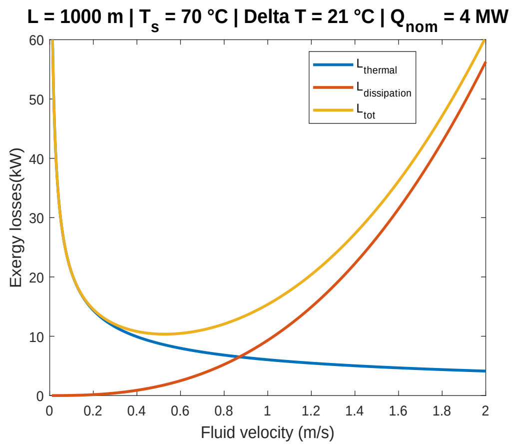

Figure 7: Distribution of exergy losses versus velocity for a design capacity of 4 MW

Figs. 6 and 7 demonstrate this point by studying the distribution of thermal exergy and viscous dissipation losses of a $4\ MW$ capacity network. Viscous dissipation losses decrease exponentially with diameter (decrease in pressure drop) while heat losses increase linearly. The optimal diameter of $330\ mm$ derived from Fig. 6 corresponds to an acceptable velocity of $0.5\ m/s$.

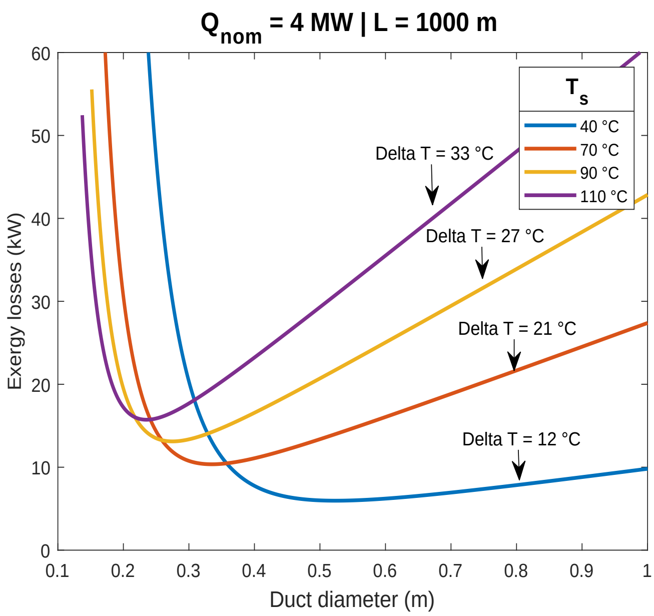

Figure 8: Variation of exergy losses versus average pipe diameter set by networks with different temperature levels

Thereafter, four network case studies with different supply temperatures are considered. Their common characteristics are a total length of $1000\ m$ and a nominal capacity of $4\ MW$. A parametric study on the supply temperature T_s is shown by Fig. 8. Knowing that low temperature networks carry higher flow rates, suitable temperature differentials are taken into account for each case. It is deduced that the sensitivity of heat losses increases sharply with the temperature level as opposed to viscous dissipation exergy losses, whose contribution is all the greater as the network temperature decreases. Furthermore, the lower the average temperature of the network, the larger the optimal diameter. This result shows that minimization of exergy losses on low temperature networks requires large diameters, as a consequence of the high flow rates conveyed and low temperature differentials. Viscous dissipation exergy losses are necessarily greater under these conditions, and therefore not negligible.

4.2. Influence of operating parameters

This section studies the evolution of exergy losses as a function of operating parameters (flow rate, temperature differential, partial power). The first network case of study in Table 2 with a supply temperature of $70°C$ and an average nominal diameter of $330\ mm$ is considered throughout this section. Its optimal diameter is obtained with Fig. 8.

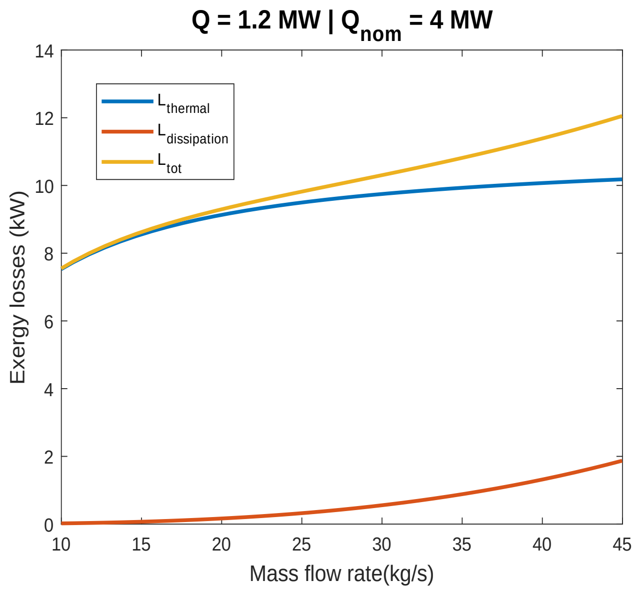

Figure 9: Distribution of exergy losses versus mass flow rate for a network power demand of 1.2 MW

The partial power operation is analyzed first. Fig. 9 gives the distribution of exergy losses for a demand on the network set at $\dot{Q} = 1.2\ MW$. It shows that exergy losses by viscous dissipation increase exponentially with flow rate.

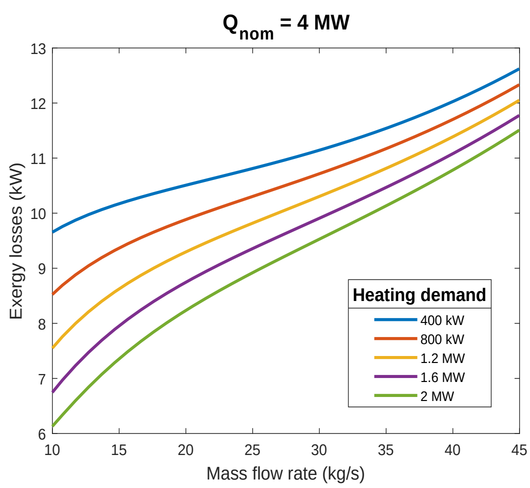

Figure 10: Variation of exergy losses versus mass flow rate at several fixed partial loads

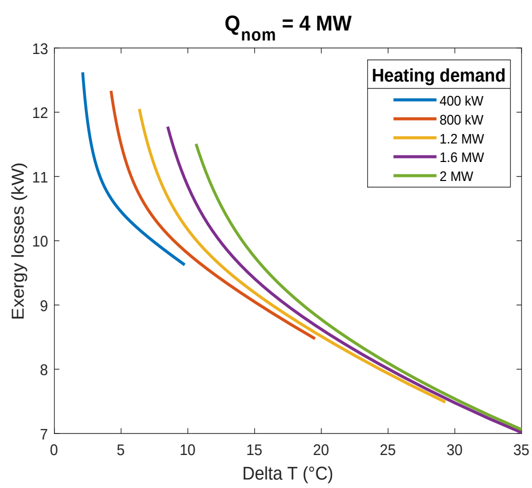

Figure 11: Variation of exergy losses versus temperature differential at several fixed partial loads

In Fig. 10, the influence of partial load operation on the evolution of exergy losses is studied more generally for loads ranging from 10 to 40% of the nominal power. Fig. 11 is derived from Fig. 10 and shows the adaptation of temperature differential to mass flow variation. They show that viscous losses become dominant as the load on the network increases. Indeed, curves of Fig. 10 tend towards the same value with increasing flow rate because the sensitivity of viscous dissipation exergy losses increases with the flow rate. Low-temperature networks are therefore highly subject to exergy losses due to viscous dissipation. Due to the low temperature differentials, they operate over higher flow ranges and thus for non-negligible viscous dissipation exergy losses.

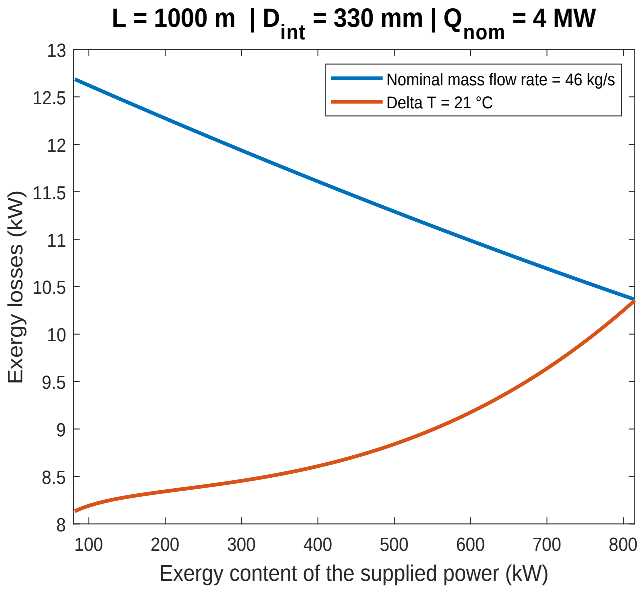

Figure 12: Variation of exergy losses versus requested exergy power on a 4 MW network $\dot{E}_p = (1 - \frac{T_a}{T})\dot{Q}$

Lastly, power regulation during operation is carried out either by acting on flow rate (with a fixed temperature differential $\Delta T_{f'}$ suitable for this case as metionned in section 4.1.) or on temperature differential (with the network's nominal flow rate fixed). Fig. 12 shows that exergy losses are lower for constant temperature differential $\Delta T_{f'}$ operation (orange curve). It represents the evolution of exergy losses as a function of **exergy power demand**. This representation choice makes it possible to better perceive the share of exergy losses and thus the evolution of the network's exergy efficiency. Exergy losses in case of a fixed flow rate (blue curve, fixed at the nominal flow rate) are constantly higher than the one at a fixed temperature differential (and therefore a fixed return temperature $T_{f'}$ at the consumer side). Operating at a constant return temperature is consequently more interesting than operating at a constant flow rate to minimise exergy losses. The latter emphasizes the need to take viscous dissipation exergy losses into account since pressure drops increase with the flow rate.

5. Application to the BlueFactory low temperature network concept

As part of the BlueCAD project led by the Thermal & Energy Laboratory, a new concept of advanced low-temperature thermal network is being proposed. The system would operate with a temperature level adjusted according to seasons thanks to a control unit enabling a smart management and integration of renewable energy sources (geothermal energy).
Several network models are considered :

1. medium-temperature networks ($60/65°C$) consisting only of heat exchanger substations for heating and hot water supply
2. intermediate temperature levels networks ($30/35°C$) that can integrate heat exchanger substations for heating and heat pump units for domestic hot water production.

Complementary heat, such as an existing high-temperature thermal network, can be added, both to compensate for the intermittent nature of renewable energy sources and to supplement the heat delivered by heat pumps. The design of a low-temperature network based on this concept is under consideration for the BlueFactory site located in Fribourg (Switzerland). It is intended to supply the 11 buildings of this 74500 m^2 district, housing the Smart Living Lab research centre (EPFL, HEIA-FR, the University of Fribourg). In addition to existing renovated buildings, new and more energy-efficient buildings will be added in the coming years. Due to this coexistence of buildings in several phases of the project, the designers considered a 4 MW capacity network. The temperature should evolve from $70°C$ to $40°C$ by 2040, when new buildings will be connected to the grid. This evolution implies that a diameter compromise must be found. Indeed, the transition to low temperature will reduce thermal losses but increase dissipation losses because of higher operating flow rates. The issue is to size the pipes by considering a $70°C$ network from the outset, (and therefore a smaller optimal average diameter), or a $40°C$ network with a larger diameter.

Table 2: Optimal conditions for two networks of $70°C$ and $40°C$

$T_s, °C$	$D_{i_{opt}}, mm$	$\Delta T, °C$	$\dot{M}_{nom}, kg/s$	Q_{nom}, MW
70	330	21	46	4
40	520	12	80	

According to the exergy methodology developed above, it is recommended to size the network with larger diameters because pressure drops are more sensitive to flow rate increase than heat losses (Fig. 10). To demonstrate the latter, the two possible operating points are compared on an exergy basis. Fig. 8 shows the diameters minimising exergy losses, i.e. 330 mm for a network with a supply temperature of $70°C$ and 520 mm at $40°C$. Fig. 13 shows the variation of exergy losses as a function of the exergy power delivered by a 330 and 520 mm average diameter network.

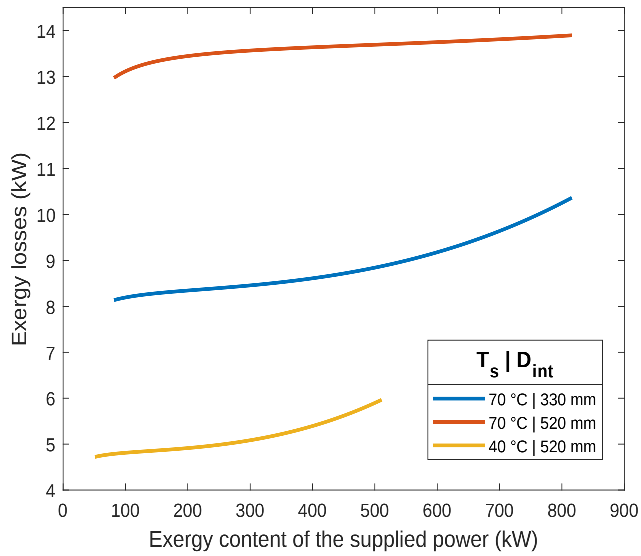

Figure 13: Variation of exergy losses versus required exergy power on BlueFactory's network according to the different configurations

The case of a $40°C$ network with a small diameter is not considered here because the flow rates conveyed are so high that the operation is outside the acceptable velocity range. Large diameters generate higher exergy losses at high temperatures due to heat losses (large exchange surface) but subsequently allow high flow rates to be conveyed, thus limiting the sensitivity of viscous dissipation exergy losses. Thus, lowering the temperature level on the larger diameter network minimizes exergy losses by reducing both heat losses and viscous dissipation losses sensitivity (transition from orange to yellow curve). Regarding exergy losses, it is therefore more interesting to work with larger diameters in order to limit the sensitivity of dissipation losses during the transition to low temperature while significantly reducing thermal losses. Finally, the sizing point chosen is based exclusively on minimizing exergy losses and hence pressure losses. If the investment costs had to be taken into account, the choice of optimum would be different, which is not in the scope of this study.

6. Conclusions and outlook

A new explicit formulation of thermal networks exergy losses as a function of design and operating parameters (diameter, length, average temperature...) has been developed. It allows several conclusions to be drawn about the exergy performance of low-temperature networks. These convey high flow rates due to low temperature differentials. Consequently, large diameters are needed to convey the required powers. The exergy approach confirms that pressure drops are not negligible as they become dominant when the flow rate increases. On the other hand, it is recommended to operate with a fixed return temperature to minimize exergy losses. Moreover, an optimal diameter as a function of the network's nominal power minimises total exergy losses. The formulation expressed by (15) must be generalized and individualized to incorporate the plurality of segments in a network, rather than an average diameter and a total length. Finally, the model must be extended to include the exergy systems and describe more precisely the internal viscous dissipation sources (elbows, confluents, valves) to accurately describe the performance of low-temperature networks.

Nomenclature

Dimensioned variables

c_p	specific heat at constant pressure, $\mathrm{J/(kgK)}$
$\dot{E}$	exergy rate, W
$\dot{E_m}$	exergy rate related to mass transfer, W
h	specific enthalpy, $\mathrm{J/kg}$
h_{int}	thermal convection coefficient, $\mathrm{W/(m^2K)}$
k	duct roughness, mm
$\dot{L}$	exergy losses (power), W
L	pipe segment length, m
$\dot{M}$	mass flow rate, $\mathrm{kg/s}$
$\dot{Q}$	thermal heat power, W
s	specific entropy, $\mathrm{J/(kgK)}$
T	temperature, $^\circ\mathrm{C}$
U	overall heat transfer coefficient, $\mathrm{W/(mK)}$
v	specific volume, $\mathrm{m^3/kg}$
$\dot{V}$	volume flow rate, $\mathrm{m^3/s}$
ν	kinematic viscosity, $\mathrm{m^2/s}$
ρ	density, $\mathrm{kg/m^3}$
λ	thermal conductivity, $\mathrm{W/(mK)}$

Operators

Δ	Difference between final and initial value
$\underline{\Delta}$	Difference between initial and final value
$\overline{x}$	average value of the variable x

Subscripts and superscripts

a	Ambient
g	Ground

i	In
ins	Insulation
int	Internal
m	Mean
nom	Nominal
opt	Optimal
o	Outer, Out
p	Pipe
s	Supply

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