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Selected technical aspects of managing efficient heat supply in a district heating system

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Abstract

District heating networks are key components of efficient heat supply systems for municipal and industrial consumers. The purpose of the research presented in this article was to analyze the thermo-hydraulic parameters of the operation of a transmission main in a district heating network to improve the heat transfer efficiency. Based on a literature review of existing studies, the basic issues of the heat supply process were discussed, and selected methods and tools for simulating district heating networks were characterized. A detailed mathematical description of the phenomena occurring during heat transport in a district heating network pipeline was also presented. Then, analytical calculations and simulations were carried out for the selected district heating system using Termis software. Operational parameters collected in the actual district heating system were used as output data for analytical modeling. Pressure drops, power losses, and heat transfer efficiencies in the main buses at different outdoor temperatures during the heating season were determined. Selected results of the study were included, and possibilities for improving the efficiency of heat transfer in the studied district heating network were indicated.

Introduction

Heat energy meets the needs of both society and industrial consumers and is an important part of any national economy. In many EU countries, especially in Eastern Europe and Nordic countries, heat is supplied to urban areas through centralized district heating systems. The fundamental idea of district heating is "to use local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local marketplace" (Werner, 2017).

From the point of view of national energy security, district heating systems (DH systems, DHS) are part of critical infrastructure and should guarantee the reliability of heat supply to consumers while limiting environmental impacts. Energy security in district heating systems is affected primarily by technical conditions, such as (Wrzalik, 2019):

- balancing the demand side (current, independent from weather conditions and perspective);
- technical condition of heating infrastructure and its reliability;
- possibility of effective management of district heating infrastructure.

DH systems should be operated in a technically and economically reasonable manner, with high energy efficiency, by reducing energy consumption and minimizing transmission losses (Rak, 2017).

Climate and energy policies, which have been implemented for several years, determine the process of decarbonization and gradual transformation of DH systems into sustainable, efficient systems with limited negative impact on the environment. Innovative developments in non-fossil energy generation technologies have led to the conceptualization of 4th generation district heating (4GDH) as part of sustainable energy systems. These are low-temperature district heating systems that use renewable energy sources, waste heat, and heat storage technologies (Lund et al., 2021). 4GDH systems provide heat supply to low-energy buildings from heating systems with low network losses (Werner, 2017). The advantages of low-temperature heat networks (LTDH) are their efficiency (reduced heat losses), increased use of stored heat, and the ability to flexibly connect and integrate multiple renewable heat sources into smart energy systems (Werner, 2017; Lund et al., 2021).

The development of district heating (DH) technologies is closely related to the improvement of design and management techniques (Ancona et al., 2019). To effectively design and implement 4GDH systems with a high share of variable renewable energy sources, dynamic numerical models and tools are needed to simulate and optimize the configuration of existing or planned district heating networks (Schweiger et al., 2017; Simonsson et al., 2021). Although the dynamic thermo-hydraulic optimization of large district heating systems is very complex and numerically difficult, advanced software exists for the detailed modeling of such district-level energy systems (Allegrini et al., 2015).

Basic issues in the control and simulation of district heating networks

In general, district heating systems consist of a heat source, a network of users, and a distribution network. Based on the mass flow of the heating medium (water) from the heat source to the consumers via the distribution network and using the capacity as heat quantity per time unit, the power balance of a district heating system can be presented in the following simplified form:

$$G \cdot c_p \cdot (T_s - T_r) - \Delta P_{\text{loss}} = \sum P_d \tag{1}$$

where G (kg/s) is the mass flow rate, c_p (kJ/kg K) is the specific heat of water, T_s (K) is the temperature of water at the source outlet to the network, T_r (K) is the temperature of return water to the source, ΔP_{loss} (kW) is the heat transmission losses, and ΣP_d (kW) is the total heat power demand of consumers.

To properly operate a system, it is necessary to draw-up a control chart to determine the optimal mass and parameters of the heating medium. Classic control of heat networks covers four issues (Vandermeulen, van der Heijde & Helsen, 2018):

- differential pressure control ensures that the pressure difference between the supply and return pipe is sufficient to ensure adequate mass flow in the periphery of the network;
- heat demand control ensures that the comfort demands of the customers are met (in buildings) – the space heating and DHW demand;
- flow control ensures that the mass flow rate is sufficiently large to deliver the demanded heat;
- supply temperature control ensures that the supply temperature in the network is sufficiently high by injecting the correct amount of heat.

The differential pressure (disposable pressure) is controlled by circulating pumps in the heat network, as shown in Figure 1 (Rak, 2017).

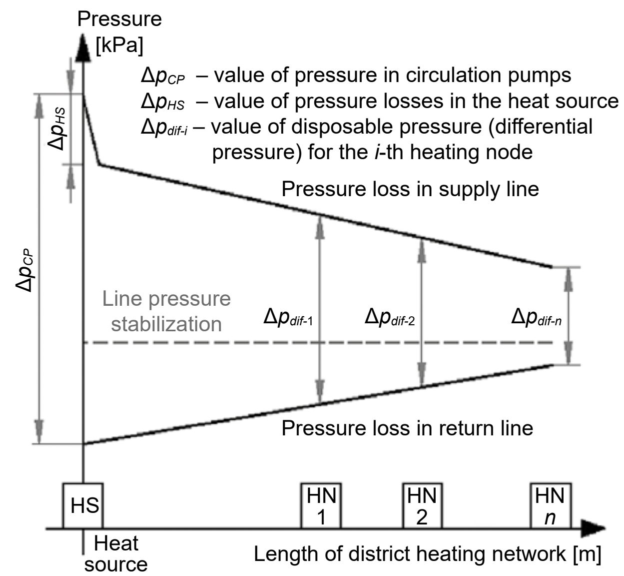

Figure 1. Pressure distribution in a district heating network

The network supply temperature is determined by curves that describe the relationship between the outdoor temperature and the heating medium temperature from the heat source. This set point temperature, in combination with the mass flow and return temperature of the network, identifies the heat that should be introduced into the network (Vandermeulen, van der Heijde & Helsen, 2018).

Matching the heat supply to demand is important for properly operating a district heating system. It requires adequate capacity installed in the heat source and a flexible response to changes in demand resulting from weather conditions. Based on the

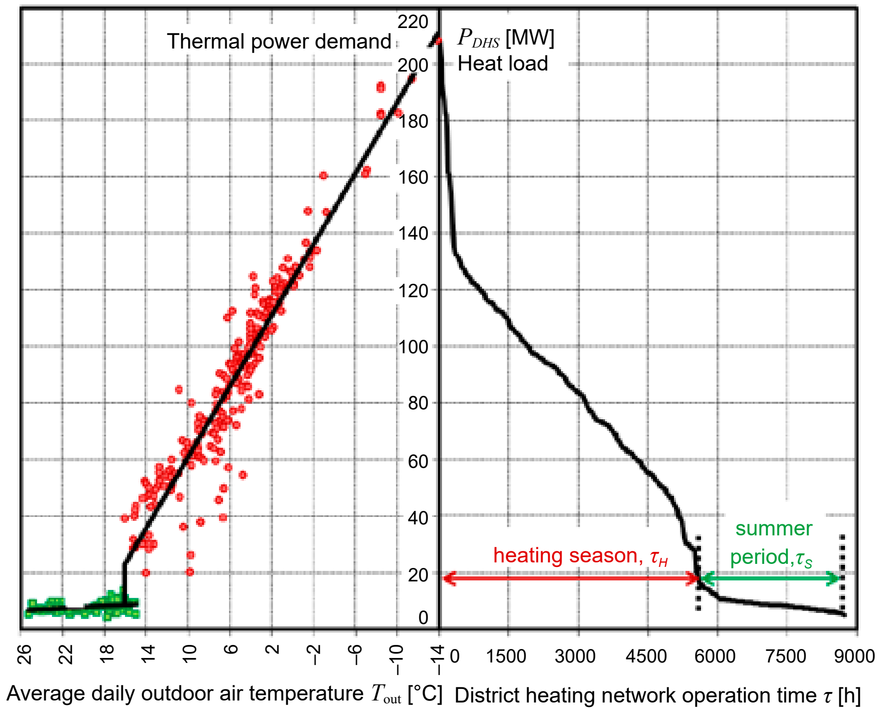

Figure 2. Ordered (cumulative) annual heat demand curves for the selected city's district heating system

power balance and outdoor temperature variations, annual heat demand charts can be prepared, which usually include two types of graphs:

- an annual graph of thermal power demand versus average daily outdoor air temperature,
- an ordered annual chart of heat load as a function of frequency (duration) of a specific outdoor temperature.

These charts for the selected district heating network are shown in Figure 2.

Classic control has a very clear advantage: it is robust. Advanced control introduces a fifth type of control, namely load control. Unlike heat demand control, which focuses on meeting customer comfort requirements, load control aims to vary the heat load of the supply to improve the efficiency of the thermal network by utilizing a thermal energy storage (TES) installed in the system. As a result of controlling the mass flow and supply temperature, the TES is charged/discharged as required. Advanced control can improve the performance of district heating systems by (Vandermeulen, van der Heijde & Helsen, 2018):

- Minimizing peaks and filling thermal valleys,
- Optimizing the operation of district heating plants,
- Enabling the operation of low-energy districts,
- Enabling low supply temperatures in a network,
- Supporting the transition to a 100% RES-based energy system.

The development of advanced control systems in thermal networks faces significant obstacles, including the size of the heating network, the uncertainty of the predictions, and the complex dynamics of phenomena. Nowadays, the most widely used is the central control of a district heating system with operational optimization using mixed nonlinear problems (MINLP). One step further is model predictive control (MPC), in which the result of operational optimization is applied to control the heat network (Vandermeulen, van der Heijde & Helsen, 2018). Realizing operational optimization and predictive control issues requires using an aggregated thermal network model using information about network parameters and the network's state (Allegrini et al., 2015; Schweiger et al., 2017; Vandermeulen, van der Heijde & Helsen, 2018; Simonsson et al., 2021).

The approach to creating a district heating network model is governed by the assumptions made, the problem to be analyzed, and the expected speed and accuracy of the calculations. In the general case, a physical model of a DH network should consider three laws: conservation of mass (mass flows), conservation of momentum (applies to pressure distribution), and conservation of energy (heat transport). If the variables (mass flow, heating medium temperature) are not functions of time, static models are built, which can be described by algebraic equations (Babiarz & Kut, 2018; Guelpa & Verda, 2019; Simonsson et al., 2021). A simple one-dimensional fluid-dynamic thermal model describing a DH network consisting of N nodes and M branches (pipes) contains the equations of conservation of mass (2a) applied to all nodes and the equations of conservation of momentum (2b) and energy (2c) to all branches (Ancona et al., 2019; Guelpa & Verda, 2019; Zimmerman, Kyprianidis & Lindberg, 2019):

$$\begin{cases} \text{a) } \sum G_{\text{in}} - \sum G_{\text{out}} = G_{\text{ext}} \\ \text{b) } \left(p_{\text{in}} - p_{\text{out}}\right) = \dfrac{f_D}{2d_i} L \dfrac{G^2}{\rho \cdot S^2} + \\ \quad + \dfrac{1}{2} \sum_k \zeta_k \dfrac{G^2}{\rho \cdot S^2} - \Delta p_{\text{pump}} \\ \text{c) } V \cdot \rho \cdot c_p \dfrac{dT_{\text{out}}}{dt} = G \cdot c_p \left(T_{\text{in}} - T_{\text{out}}\right) - u \cdot L\left(T_{\text{in}} - T_a\right) \end{cases} \tag{2}$$

where ΣG_{in} and ΣG_{out} are the sum of the mass flow rates entering or leaving the i-th node, respectively, G_{ext} is the mass flow rate outward from the node (for open networks only), p_{in} and p_{out} (Pa) are the pressures at the inlet and outlet of the j-th pipe, respectively, f_D is the Darcy friction factor, d_i (m) is the inner diameter of the pipe, L (m) is the length of the pipe, ρ (kg/m^3) is the density of the fluid in the pipe, S (m^2) is the cross-sectional area of the pipe, $\Sigma\zeta_k$ is the sum of the local pressure loss coefficients, Δp_{pump} (Pa) is the pressure rise provided by the pumping stations located along the network, V (m^3) is the volume of the pipe, T_{in} and T_{out} (K) are the fluid temperatures at the inlet and outlet of the j-th pipe, respectively, u (kW·m^{-1}·K^{-1}) is the overall heat transfer coefficient governing the radial heat transport from the fluid to the environment, and T_a is the ambient temperature (ground or air).

The mass balance equation (2a) in matrix form allows us to calculate the mass flow rate in each branch of the network. In this matrix, the number of rows equals the number of nodes (N), and the number of columns equals the number of branches (M). The overall element of the matrix, $\boldsymbol{A}_{\mathbf{ij}}$, is equal to 1 if the mass flow in branch j flows into node i or –1 if it flows out of it, and 0 if pipe j has no connection to that node (Babiarz & Kut, 2018; Guelpa & Verda, 2019). The left side of equation (2c) represents the rate of energy stored in the water in the segment (pipe) as the product of the fluid mass $V{\cdot}\rho$, the specific heat capacity c_p, and the temperature derivative T_{out} over time (dT_{out}/dt). On the right side, the first component accounts for the net enthalpy flow associated with the fluid mass flow rate G, while the second component corresponds to the heat conduction to the environment through the metal wall and the insulation material of the pipe (Ancona et al., 2019).

The system of equations (2) was formulated assuming typical simplifications (van der Heijde, Aertgeerts & Helsen, 2017; Guelpa & Verda, 2019):

- water is incompressible,
- the specific heat of water is constant,
- velocity changes within a single pipeline are neglected,
- heat conduction along pipelines is neglected,
- fluid temperature is uniform across the pipe cross-section,
- the gravitational component of static pressure has been neglected,
- temperature change of pipe material is neglected.

In new DH technologies, the increasing use of renewable energy sources, along with the need to improve the efficiency of heat delivery, were determinants for the development of DH system management methods (e.g., optimization, predictive control), taking into account the dynamic models of these systems (Schweiger et al., 2017; Zimmerman, Kyprianidis & Lindberg, 2019). The development of dynamic DHN models makes it possible to observe the transient behavior of heat propagating through the network without physically interfering with its structure. Accounting for temporal variations in temperature, pressure, and heating medium flow in network modeling is important for effectively managing DH systems because practice and research indicate that (Schweiger et al., 2017; Wang et al., 2017; Guelpa & Verda, 2019; Simonsson et al., 2021):

- both the temporal and spatial behaviour of the network must be considered in the transition to renewable energy sources and lower-temperature DH networks;
- mass flow distributions vary significantly depending on heat demand, pumping strategy, and network topology;
- time delays in a network affect the amount of heat lost to the surroundings and must be taken into account in intelligent DH management algorithms;
- thermal losses can significantly affect the temperature distribution in a network, especially in large DHNs during low thermal loads (hot water supply).

One of the tools used in research to create dynamic models of DHN is the MATLAB®/Simulink® environment (Wang et al., 2017; Ancona et al., 2019). The physical model created in this program takes into account both thermal dynamics and heat transfer fluid dynamics of the distribution pipe. MATLAB®/Simulink® can simulate the thermodynamic behavior of simple systems under both steady-state and transient conditions, but its use is limited to causal modeling (Simonsson et al., 2021).

Although existing district heating networks are complex networks of pipes with different diameters and lengths, and the dynamic thermo-hydraulic optimization of large-scale district heating systems is very complex and numerically difficult, there are currently a number of advanced programs on the market for detailed DH modeling and optimization. Tools such as Termis, TRNSYS, PSS SINCAL, and Netsim are widely used for DH network simulation (Allegrini et al., 2015, Simonsson et al., 2021). Termis is a powerful simulation platform for improving the design and operation of district heating systems. An important feature of Termis software is its ability to calculate heat losses in distribution networks based on pipe parameters and data concerning the temperature and pressure of water in the network. This makes it possible to identify heating lines that require modernization – insulation or the replacement of pipes with pre-insulated ones.

Physical model of district heating pipeline

Pipes are the main components of district heating systems. The pipe model, as part of a network, must take into account the thermo-hydraulic phenomena related to the flow of the heating medium, i.e., mass flow-dependent transport delays, pressure losses, and heat losses (Schweiger et al., 2017).

Due to the extent of district heating networks, hydraulic simulations are based on simple equations (2b) describing linear pressure losses and local losses. Based on such equations and the mass balance at each node, it is possible to determine the pressure and water flow at each point in the network under given boundary conditions, i.e., the supply pressure. In the general case, the total pressure change Δp in a pipeline segment is the sum of distributed pressure losses due to friction, pressure drops due to gravity, and local pressure losses (the presence of orifices, valves, elbows, etc.). The pressure changes Δp in a pipe according to the algorithm adopted in Termis is given by the following formula (Schneider Electric, 2012):

$$\Delta p = -\rho \frac{f_D}{2d_i}|v|v \cdot L + g(Z_d - Z_u)\rho - \frac{1}{2}\sum_k \zeta_k \cdot \rho |v| v \tag{3}$$

where v (m/s) is the fluid velocity, g (m/s^2) is the acceleration due to gravity, Z_d (m) is the pipe outlet elevation, and Z_u (m) is the pipe inlet elevation.

The fluid velocity v is defined by relation (4):

$$v = \frac{G}{\rho \cdot S} \tag{4}$$

The friction factor f_D is calculated from the Colebrook-White formula (5):

$$\frac{1}{\sqrt{f_D}} = -2 \cdot \log\left(\frac{2.51}{Re\sqrt{f_D}} + \frac{k}{3.71 d_i}\right) \tag{5}$$

where k (m) is the pipe wall roughness, and Re is the Reynolds number determined from relation (6):

$$Re = \frac{v \cdot d_i \cdot \rho}{\mu} \tag{6}$$

In equation (6), the quantity μ (Pa·s) is the dynamic viscosity of the fluid. Because determining the friction factor f_D by the Colebrook-White formula requires iterative calculations, one can use Churchill's formula (7) to give a direct result (Hermansson et al., 2018; Zimmerman, Kyprianidis & Lindberg, 2019):

$$f_D = 8\left[\left(\frac{8}{Re}\right)^{12} + \frac{1}{(\omega_1 + \omega_2)^{1.5}}\right]^{1/12} \tag{7}$$

where

$$\omega_1 = \left[-2.457 \ln\left(\left(\frac{7}{Re}\right)^{0.9} + 0.27\frac{k}{d_i}\right)\right]^{16}$$

and

$$\omega_2 = \left(\frac{37530}{Re}\right)^{16}.$$

The essence of the phenomena occurring during heat transport in a DHS pipeline according to the conservation of energy equation (2c), i.e., excluding hydraulic effects, is shown in Figure 3 (Wang et al., 2017).

The individual quantities in Figure 3 represent: q_1 is the heat carried into the element, q_2 is the heat carried out from it, q_{loss} is the heat lost to the surroundings, x is the spatial coordinate along the length of the pipe, T is the temperature along the x-coordinate, and t is time.

Based on the principle of heat balance, the following equation can be derived to describe changes in the temperature of a fluid moving through a pipe (Wang et al., 2017):

$$\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial x} + \frac{u}{S\rho c_p}(T - T_a) = 0 \tag{8}$$

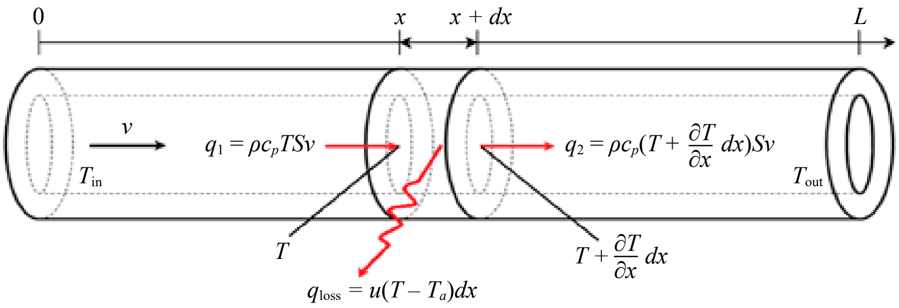

Figure 3. Heat transport in a district heating system pipeline

Assuming positive flow and a linear dependence of heat loss on $T(x) - T_a$, the temperature at the outlet of the pipe is (Schweiger et al., 2017; Wang et al., 2017):

$$T_{\text{out}}(t) = T_a + [T_{\text{in}}(t-\tau) - T_a] e^{-\frac{u}{S\rho c_p}\tau} \quad (9)$$

where $\tau = L/v$ is the time interval for the mass flow from the pipe inlet to the pipe outlet.

Energy transport through the pipeline and associated heat losses to the environment, considering hydraulic phenomena, result from the combination of the energy equation. The continuity equation with the internal energy of the heating medium as a function of the axial position in the pipe x and time t is (van der Heijde, Aertgeerts & Helsen, 2017):

$$\underbrace{\frac{\partial (S\rho c_p T)}{\partial t}}_{\text{time derivative}} + \underbrace{\frac{\partial \left(S\rho v \left(c_p T + \frac{p}{\rho} \right) \right)}{\partial x}}_{\text{spatial derivative}} = \underbrace{vS\frac{\partial p}{\partial x}}_{\text{pressure difference energy}} + \underbrace{\frac{1}{2}\rho v^2 |v| f_D C}_{\text{wall friction dissipation}} + \underbrace{\frac{\partial}{\partial x}\left(\lambda_w S \frac{\partial T}{\partial x} \right)}_{\text{axial heat diffusion}} + \underbrace{-u(T-T_a)dx}_{\text{heat losses}} \quad (10)$$

where p (Pa) is the absolute pressure, C (m) is the pipe circumference, λ_w ($\text{kW}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$) is the thermal conductivity of the fluid in the pipe, and $\partial p/\partial x$ is the pressure gradient.

The algorithm used in Termis for calculating the temperature distribution in a district heating network is based on equation (10) and neglects axial heat diffusion. Analyses reported in the literature (van der Heijde, Aertgeerts & Helsen, 2017) show that heat diffusion can be neglected over virtually the entire operating range of heat network pipes (i.e., a high Péclet number due to existing pipeline lengths and flow velocities). The vast majority of studies have also ignored the effects of pressure loss and wall friction (Schweiger et al., 2017; Wang et al., 2017; Ancona et al., 2019). However, in the Termis program, the temperature T_{out} at the outlet of the pipe is determined according to equation (Schneider Electric, 2012):

$$T_{\text{out}} = \frac{A}{B} + \left(T_{\text{in}} - \frac{A}{B} \right) e^{-\frac{B \cdot L}{v}} \quad (11)$$

where

$$A = \frac{1}{\rho \cdot c_p} \left[v\frac{\partial p}{\partial x} + \rho \frac{2 f_D}{d_i} |v| v^2 + u\frac{T_a}{S} \right]$$

and

$$B = \frac{1}{\rho \cdot c_p} \cdot \frac{u}{S}.$$

In further studies, according to equation (11), it was assumed that changes in temperature of the heating medium between the inlet and outlet of the pipeline depended on its initial temperature, residence time in the pipe, pressure drop, and heat due to friction of the fluid against pipe walls.

Experimental results

The purpose of this study was to analyze the thermal-hydraulic conditions and heat transfer efficiency of the main overhead pipelines of the city's district heating network. The parameters of these pipelines are given in Table 1.

Table 1. Parameters of the main lines of the district heating network

Direction	L (m)	d_i (m)	u ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)		k ($\text{m}\cdot 10^{-3}$)
			supply	return	
North	2190	0.7	1.7	2.5	1.5
South	1300	0.5	2.6	3.8	0.5

This study used historical process data on the operation of the district heating system in a medium-sized

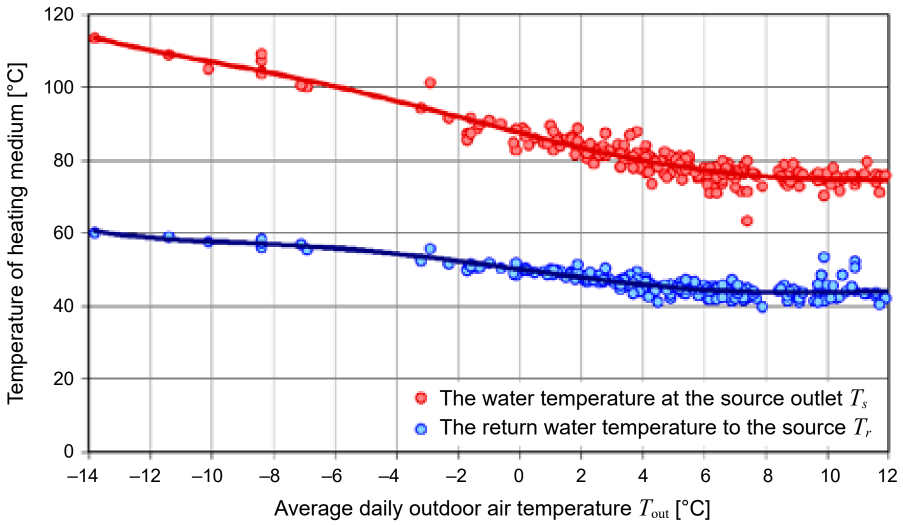

Figure 4. Changes in supply and return temperatures in the studied district heating network as a function of ambient temperature

city (approx. 200 thousand inhabitants) for a period of one year (heating season from September 17 to May 7 following year and summer period from May 8 to September 16) obtained from the heating company. These were average daily data on heating medium parameters at the heat source level, i.e., supply temperature and pressure T_s and p_s, return temperature and pressure T_r and p_r, outdoor air temperature T_{out}, mass flux G, and heat Q_{DHS} delivered to the network.

Changes in heat demand Q_{DHS} and supply and return temperatures as a function of outdoor temperature T_{out} during the heating season are shown in Figures 2 and 4.

The district heating system included two areas fed from a single source by two main lines: one in the North direction and the other in the South direction (Table 1). Knowing the proportions of the mass flow distribution from the source in both directions, the flow velocities in the DH mains were determined according to equation (4), taking into account the dependence of water's density on its temperature. The results of calculations for the heating season as a function of ambient temperature are shown in Figure 5, along with the pressure p_s at the supply. It was found that the velocities increased as the ambient temperature decreased, reaching a maximum constant value resulting from the capacity of the circulation pumps at a maximum pressure of 0.94 MPa. This is the result of the qualitative-quantitative regulation of the amount of heat transferred to the network depending on weather conditions (positive temperatures – flow rate G, negative temperatures – supply temperature T_s).

Then, using relations (3) to (7), pressure drops in the main pipelines and differential pressures at their ends were determined. Determining the value of the Reynolds number Re, the variation of density ρ, and dynamic viscosity μ of water from its temperature was taken into account. The calculated pressures during the annual period (heating and summer seasons) as a function of flow rate are shown in Figure 6, in which the pressure drops at the same flow rates were higher in the northern main, which is caused by a greater roughness of the pipes in service (about 50 years). As a result, the differential pressure at the end of the northern main dropped below 0.4 MPa in winter.

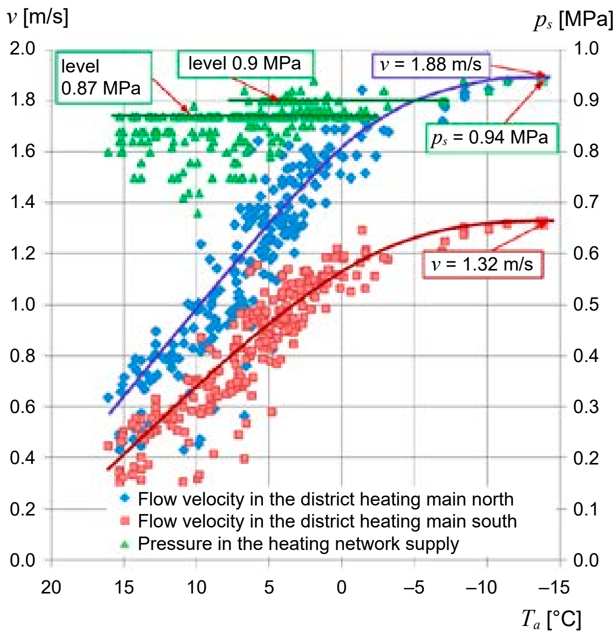

Figure 5. Changes in flow velocity in district heating mains during the heating season as a function of ambient temperature

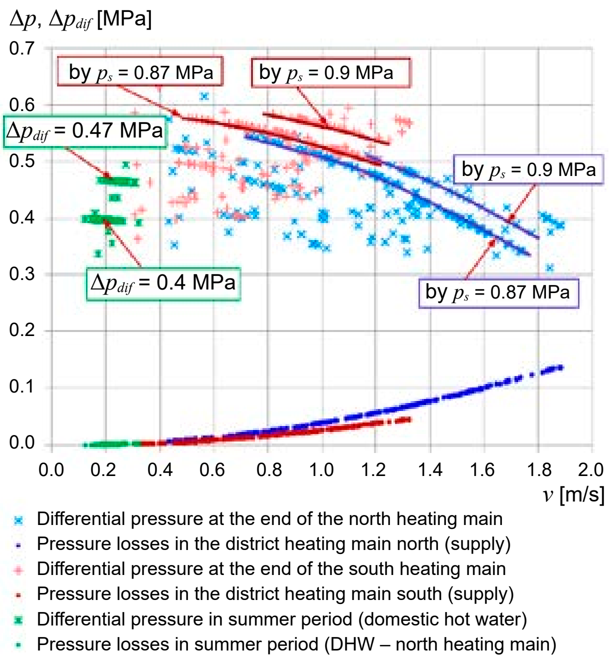

Figure 6. Pressure losses and differential pressures in district heating mains as a function of flow rate (heating season and summer)

Based on knowledge of hydraulic conditions, the temperatures T_{out} at the ends of the mains and the temperature drops ΔT in the pipelines were determined according to equation (11). The results of calculations as a function of flow rate for pipelines feeding the DHN are shown in Figure 7.

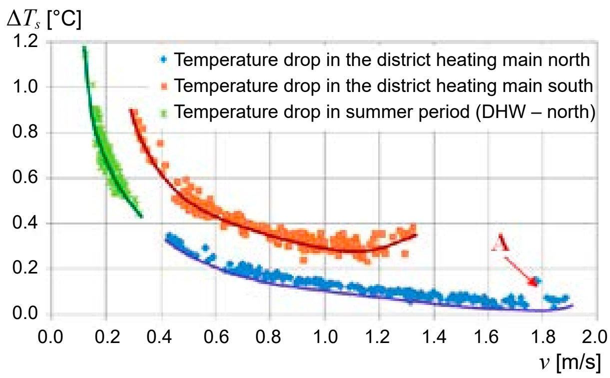

Figure 7. Temperature drops in district heating mains during the heating season and summer as a function of flow rate

The temperature drop of the heating medium increased as the flow rate decreased (longer flow time through the pipeline). Especially large temperature drops occurred in the northern main, which operates in the summer (hot water supply). In contrast, during the heating season, larger temperature drops were observed in the southern main (worse insulation).

The final stage of the research involved determining the thermal power losses in the district heating mains according to the relationship $\Delta P_{HM} = u \cdot L \cdot (T_{in} - T_a)$ from equation (2c) and the heat transfer efficiency η_{HM} defined as the power losses in the district heating main to the power P_{HM} transferred through the main. The calculated results are shown in Figures 8 and 9.

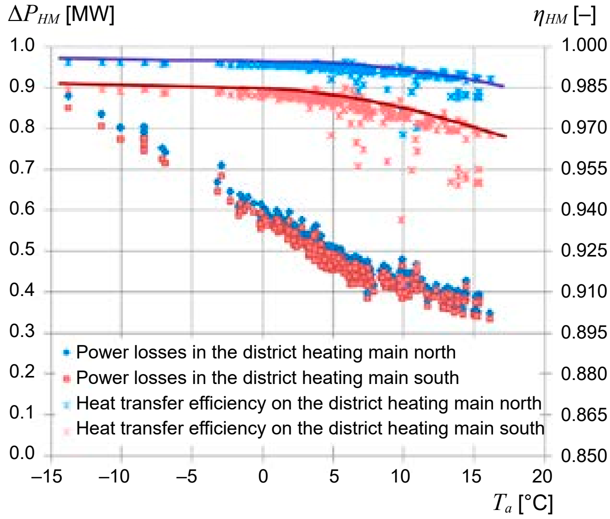

Figure 8. Power losses and heat transfer efficiency of district heating mains during the heating season as a function of ambient temperature

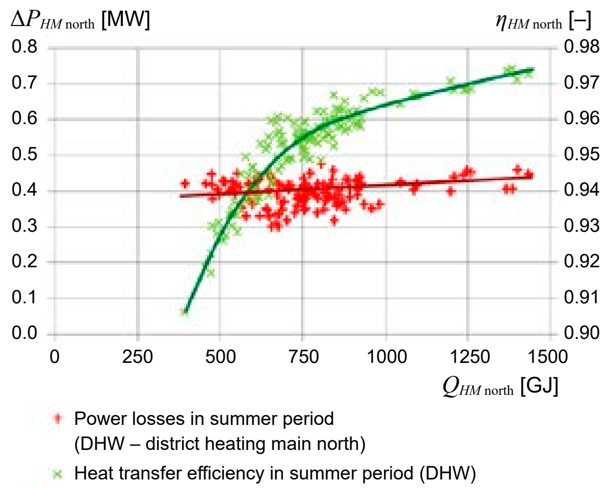

Figure 9. Power losses and heat transfer efficiency in the north heating main in the summer as a function of heat demand (DHW)

During the heating season, the amount of power losses ΔP_{HM} increased as the ambient temperature decreased. Comparing the values of losses in the two heating mains for the same temperature shows that they were almost equal because the southern main, although shorter, has worse thermal insulation. On the other hand, the heat transfer efficiency in this line was much lower, as it carried almost three times less thermal power with comparable losses. Therefore, it should be thermally upgraded. A comparison of the waveforms in Figures 2 (power demand) and 8 shows that the transfer efficiency decreased as the thermal load on the heating main decreased. This can be seen in Figure 9 for the transport of hot water through the northern main in summer. Given the high level of distributive heat losses and pressure drops caused by the great roughness of the pipe walls (compared in Table 1), this mainline should also be replaced with a new one made with pre-insulated technology.

Summary and conclusion

The case study presented in this article deals with issues that determine the heat transmission efficiency in a district heating system. The purpose of the study was to analyze the thermal-hydraulic parameters of the main transmission lines in a selected urban district heating system and to identify activities necessary to improve the heat delivery efficiency. A detailed literature review was carried out on the mathematical description of hydraulic phenomena and heat transport in pipelines, taking into account modern tools for modeling district heating systems. It was decided to use a non-standard approach to account for hydraulic phenomena during the transport of the heating medium in the pipe, i.e., pressure drops along the pipeline and heat resulting from friction of the fluid against the pipe walls. Operational data collected in a real district heating system covering a period of one year (heating season and summer period) and geometric and thermal parameters of the studied pipelines were the outputs of analytical calculations.

Appropriate mathematical calculations were carried out, and the pressure drops, temperature drops, power losses, and heat transfer efficiencies in the mains were determined. Then, the dependencies on ambient temperature and flow rate were indicated. The dependence of the temperature distribution in the studied DHN and heat losses on the network load, i.e., on the power demanded by consumers, was confirmed.

During the evaluation of the calculation errors, it was found that pressure drops were most affected by the pipe roughness k and local resistances, e.g., a 20% change in roughness resulted in a 5.6% change in pressure drop. Temperature drops and power losses depended mainly on the heat transfer coefficient to the environment – a 10% increase in u resulted in a 5.5% increase in losses and a 24% increase in temperature drops. However, neglecting hydraulic phenomena results, for high flow velocities v, in an error in the determination of the temperature drop exceeding 100% (point A in Figure 7).

The analyses indicated the factors influencing the amount of heat and pressure losses and made it possible to conclude that the main heating mains of the network under study require thermal modernization or replacement with new ones made with pre-insulation technology.

The developed methodology can also be applied to other DH systems, as long as data on heat transfer parameters (pressure, medium temperature, mass flow rates) are available, as well as the quantities characterizing the pipeline given in Table 1.

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