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HYDRAULIC ANALYSIS OF A DISTRICT HEATING NETWORK

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ABSTRACT

The aim of this work is to study the influence of pressure loss parameters from a district heating system on the distribution of fluid flow rates.

The research was finalized by improving the mathematical model of a district heating network, which comprises an algebraic non-linear system that synthesizes flow balance equations of a stationary flow. This enhanced model indicates the influence of every consumer's heat demand supplied from a district heating network on the fluid flow rates distribution based on the means of the implicit function theorem. The originality of the method consists of considering the network a sensitive system that responds to the variations of input parameters (pressure loss parameters) by variations of output parameter (fluid flow rates).

The main advantage is that the engineer in charge with exploitation of the heating system may understand what happens with the flow allocations when pressure loss parameters of the network are different from the nominal ones, without making any measurements on the field or computations using new scenarios. The method presented in this paper facilitates the choice of the best decision concerning balancing and practical management of radial heating networks.

NOMENCLATURE

$H(q)$	pump head [MPa]
$q_1, q_2, \dots q_m$	fluid flow rates [l/s]
$M_1, M_2, \dots M_p$	pressure loss parameters [MPas^2/l^2]

Matrices and vectors

A	matrix of influence (m x p)
q	vector of the fluid flow rates (m x 1)
M	vector of the pressure losses (p x 1)

Superscript

n	nominal (designed) value

1. INTRODUCTION

In the densely populated cities, district heating together with combined heat and power production has been demonstrated to be the least-cost heating option on long term with respect to energy efficiency, saving energy and lower carbon dioxide emissions. The annual heat turnover of district heating systems in the entire world adds to approximately 11EJ [1]. This technology supplies heat to more than 100 million people in Europe (Russia excluded) [2]. There are important differences between Eastern and Western DHS both on the level of modern equipments and the conception of design and operating.

In most Western European countries, customer substations located in the connected buildings transfer heat from the network to the building heating system. The entire district heating system is regulated by the demand using control equipment at four independent levels: two at the customer and two managed by the district heating operator. Each building usually has separately regulated systems for supplying heat to the radiators, to the domestic hot water distribution system and to the ventilation system. The main advantage of this concept is that customers adjust the heat demands by means of thermostatic valves at the first level of heat demand control, avoiding the risk that the District Heating Company delivers more heat than necessary.

The approach is different in most district heating systems from Eastern European countries: the District Heating Company establishes the quantity of hot water and the supply temperature, and delivers it into a so-called primary circuit. The primary circuit is a distribution-closed network of pipes that supply substations located in different locations all over the city. Each building is connected to the substation by a four-pipe system: one two-pipe secondary circuit connected to the radiators and one two-pipe circuit for distribution of domestic water. The buildings connected to the substation must share the quantity of heat delivered from the substation as close as possible to the heat demands. Inside the building, lack of control systems at the customers creates difficulties in having properly flow allocations. Outside the building, there is a balance of flows at nominal values by fixed orifices, according to pressure differences between the supply and the return pipes connected to each building. The excessive pressure differences, which have to be dissipated by local hydraulic resistances, do not usually match with the real values. Even if financial funds are not available for a complete modernization, at least changes of some fixed orifice devices or installations of valves in key areas of the network are necessary.

The aim of this paper is to find a numerical method able to offer quantitative and qualitative information about fluid flow allocations, whenever the real and nominal pressure losses are different. Balance equations are considered as a system of implicit equations having pressure losses as input parameters and fluid flow rates as output parameters. According to the implicit function theorem, the values of output parameters can be calculated using a matrix. In addition to being a computing tool, the matrix of influence also points out qualitative information about the sensitivity of the system. A numerical simulation for a secondary district heating system with ten buildings was performed. Validation confirms a good match with the fluid flow rates values obtained by solving the classical system of explicit balancing equations corresponding to the same network.

2. THEORETICAL BASIS

In the Eastern European countries the heat transmission network are operated in a radial mode. In the radial system, only one heat source is allowed to supply heat to the network at the time, so the substations can obtain heat from only one direction. Usually, the flows are distributed using fixed orifices. In the primary circuit, only this system is used. Modernization of some substations by controlling the temperature of hot water, according to the outside temperatures, and providing variable fluid flow rates by variable speed pumps, changed somehow the mentality about balancing of secondary circuits. Most customers have nowadays the option to modify the received heat by the means of thermostatic valves or simply by manual actions. Balancing valves are needed in buildings and in the secondary network. Since financial funds are not always available, balancing schemes recommended by the Western European technical literature [3] are not always adequate. Specific methods for specific problems that arise in partially modernized installations are needed. This paper proposes a method that can identify the most sensitive areas of a district heating network in order to intervene there for a better flow allocation with reduced costs.

The district heating pipeline network consists of supply lines that transport hot water, and return lines that conduct cooled water, from the consumers back to the heat source. Radial district heating networks may be considered binary systems, because the direction of flows is known in each circuit.

Hydraulic calculations are required to settle the local resistance needed for an adequate flow allocation. Models for calculating the steady state incompressible fluid flow rates use balance equations formulated for each close loop within the network [4-6]. The set of algebraic equation are non-linear due to the non-linear relation between the friction or local pressure loss, and the turbulent fluid flow velocity.

In order to analyse the response of a heating system at small variations of local pressure loss coefficients, a network described by flow rates into branch pipes $q_1, q_2, \ldots q_m$ and pressure loss parameters $M_1, M_2, \ldots M_p$ is studied. Pressure loss parameters may be friction losses along pipes or local losses due to fixed orifice devices, vanes, radiators, fittings, apparatus from the heating substations, etc.

An algebraic non-linear system (1) synthesizes equations of stationary flow for a heating network

$$\begin{cases} F_1\left(q_1, q_2, \ldots q_m; M_1, M_2, \ldots M_p\right) = 0 \\ \vdots \\ F_m\left(q_1, q_2, \ldots q_m; M_1, M_2, \ldots Mp\right) = 0 . \end{cases} \quad (1)$$

In the design stage, the nominal pressure loss parameters $\mathbf{M}^n = \left(M_1^n, M_2^n, \ldots M_p^n\right)$ corresponding to the nominal fluid flow rates $\mathbf{q}^n = \left(q_1^n, q_2^n, \ldots q_m^n\right)$, are computed, in order to find the preset values for the hydronic balancing.

A well-designed installation can give an equitable distribution of nominal flows by means of balancing devices. Practically, even full-modernized installations employing balancing valves, use some adjustments on the field, for the following reasons:

- pressure drops dues to friction losses are not calculated very accurately since some parameters (such as pipe roughness) are only estimated;
- pressure drops due to local losses in valves, radiators, fittings and accessories depend on the manufacturer;
- final installation is different from the initial design project.

Real values of pressure loss parameters different from nominal values means that fixed orifices already installed must be changed or that balancing valves must be adjusted. For a better flow allocation, the best areas in the network to do these changes must be identified. Identification can be done using the nominal parameters and the matrix of influence [7]. The matrix identifies which branches will have the higher influence on a new distribution, and facilitates the choice of the best decision concerning practical management of the heating networks.

The originality of the method consists of considering the network as a sensitive system that responds to variations of input data by variations of output data. The output data of the heating system $q_1, q_2, \ldots q_m$ may be calculated by using a system of implicit equations

$$\begin{cases} q_1 = f_1\left(M_1, \ldots . M_p\right) \\ \vdots \\ q_m = f_m\left(M_1, \ldots . M_p\right) \end{cases}, \qquad (2)$$

which verifies the conditions

$$q_i^n = f_i\left(M_1^n, M_2^n, \ldots . M_p^n\right), \quad i = \overline{1, m}. \qquad (3)$$

For low variations of the loss pressure parameters a linear approximation can be used

$$\begin{bmatrix} q_1 \\ \vdots \\ q_m \end{bmatrix} = \begin{bmatrix} q_1^n \\ \vdots \\ q_m^n \end{bmatrix} + \mathbf{A} \cdot \begin{bmatrix} M_1 - M_1^n \\ \vdots \\ M_p - M_p^n \end{bmatrix}. \qquad (4)$$

A is defined as the matrix of influence and may be calculated with the formula

$$\mathbf{A} = \begin{bmatrix} A_{11} & \cdots & A_{1j} & \cdots & A_{1p} \\ \vdots & & \vdots & & \vdots \\ A_{i1} & & A_{ij} & & A_{ip} \\ \vdots & & \vdots & & \vdots \\ A_{m1} & & A_{mj} & & A_{mp} \end{bmatrix}. \qquad (5)$$

where the elements $A_{ij} = \frac{\partial f_i}{\partial M_j}\left(\mathbf{M}^n\right)$.

The differential coefficients from the above formula are sensitivity coefficients and can be computed using the implicit functions theorem,

$$\begin{cases} A_{1j} = \dfrac{\partial f_1}{\partial M_j} = -\dfrac{\dfrac{D\left(F_1, F_2, \ldots F_m\right)}{D\left(M_j, q_2, \ldots q_m\right)}\left(q^n, M^n\right)}{\dfrac{D\left(F_1, F_2, \ldots . F_m\right)}{D\left(q_1, q_2, \ldots . q_m\right)}\left(q^n, M^n\right)} \\ \vdots \\ A_{mj} = \dfrac{\partial f_m}{\partial M_j} = -\dfrac{\dfrac{D\left(F_1, F_2, \ldots F_m\right)}{D\left(q_1, q_2, \ldots q_{m-1}, M_j\right)}\left(q^n, M^n\right)}{\dfrac{D\left(F_1, F_2, \ldots F_m\right)}{D\left(q_1, q_2, \ldots q_m\right)}\left(q^n, M^n\right)} \end{cases} \qquad (6)$$

Every term A_{ij} of the matrix illustrates the influence of the pressure loss parameter M_j on the fluid flow rate q_i.

This method allows us to gather information and finally optimize the changing of some local resistances for adjustments of the fluid flow rates according to nominal values. This information is primarily important if the balancing is performed with fixed devices, or limited funds prohibit too many changes, but also for reducing the costs in general.

3. NUMERICAL SIMULATION

The presented method was implemented using MATLAB software. First, the program calculates the pressure loss parameters of the transportation pipelines and the nominal fluid flow rates,. and then, using the system of equations (1), it calculates the consumers' pressure loss parameters. Flexibility is one of the advantages of the software, due to the symbolic toolbox from MATLAB. The program can be used to establish the values of the terms from the matrix **A** for different configurations of networks having different characteristics of consumers. By means of equation (4), the program can calculate new values of fluid flow rates when the loss parameters are modified.

A numerical simulation of a real secondary circuit was done. The studied district heating pipeline network is presented in fig. 1. The main secondary circuit having pressure loss parameters on the transportation pipelines denoted $M_{11}, \ldots M_{14}$ branches out in two circuits: one having pressure loss parameters on the transportation pipelines denoted M_{15}, M_{16} M_{17}, and the other denoted M_{18}, M_{19}, M_{20}. The circuit supplies with heat ten buildings where the pressure loss parameters are denoted M_1,..M_{10}. Real data concerning the length and the diameters of pipes were used for the calculation of matrix **A**, using the equations (6). A matrix of influence with 20 columns and 20 rows is obtained. The terms of the matrix concerning the influence of the pressure loss parameters of the buildings, denoted M_1,…M_{10} on the fluid flow rates q_1, …q_{10} passing through the consumers' heating installations are presented in table 1.

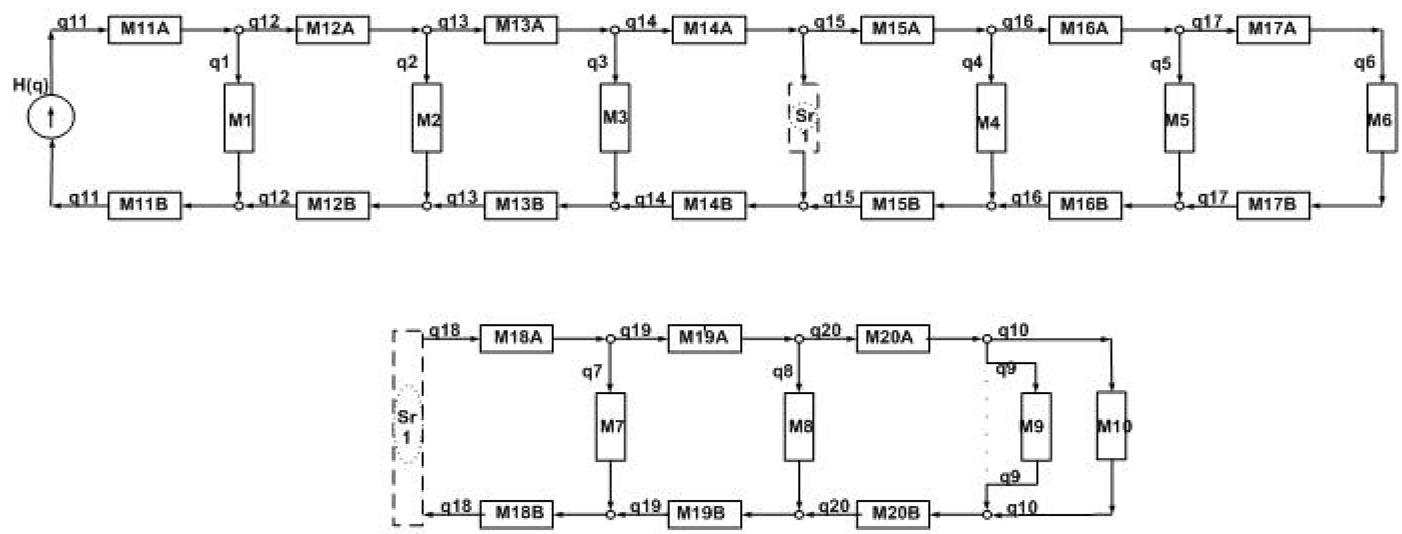

Fig. 1. Loop configuration of the secondary district heating circuit.

Table 1. Main terms of the matrix of influence

	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9	M_{10}
q_1	-20.4415	-0.00302947	-0.00049015	-0.00637785	-0.00002981	-0.00019988	-0.0030295	-0.00034715	-0.00471891	-0.000674634
q_2	-0.00748109	-5.30183	0.000690466	0.00898434	-0.00004199	0.00028158	0.0042676	0.000489033	0.00664744	0.000950343
q_3	-0.00407648	0.00232542	-0.897782	0.0594909	0.000278062	0.00186452	0.0282584	0.00323819	0.0440168	0.00629281
q_4	-0.00958812	0.00546951	0.0107536	-11.8342	0.00134438	0.00901462	0.0966936	0.0110803	0.150615	0.0215325
q_5	-0.00160311	0.00091449	0.00179798	0.0480908	-0.0565822	0.00203804	0.161669	0.0018526	0.0251825	0.00360019
q_6	-0.003023	0.00172446	0.00339047	0.0906853	0.000573143	-0.377601	0.0304862	0.00349347	0.0474869	0.0067889
q_7	-0.00748111	0.00426757	0.00839048	0.15883	0.000742376	0.00497792	-6.08277	0.320366	0.435475	0.0622572
q_8	-0.00363371	0.00207284	0.00407541	0.0771467	0.000360586	0.00241787	0.135793	-0.755726	0.369398	0.0528106
q_9	-0.00867207	0.00494695	0.00972622	0.184115	0.000860559	0.00577039	0.324078	0.0648561	-9.93807	0.17461
q_{10}	-0.00453452	0.0025867	0.00508572	0.0926716	0.000449976	0.00301727	0.169457	0.339125	0.638633	-1.50409

Table 2. Variations of fluid flow rates in the network if the pressure loss parameter M_6 increase with 50%

q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9	q_{10}
-0.0000727	0.000102461	0.000678455	0.00328022	0.000741597	-0.1374	0.00181135	0.000879808	0.00209971	0.00109792

The matrix offers quantitative and qualitative information about flow allocation in the network.

Quantitative information means, for instance, to find the unknown values of the pressure loss parameters at the consumers M_1,…M_{10} , when the differences between real and nominal values of pressure loss parameters on the branches M_{11},…M_{20} are known by measurements on field. This information is essential in hydraulic balancing. The numerical simulation using equation (4) assumed higher roughness on pipes than the one designed, therefore the real pressure loss parameters M_{11},…M_{20} inputted have higher values. The required additional pressure loss parameters at consumers, M_1,…M_{10}, were calculated (by means of the matrix **A**), to maintain the nominal fluid flow rates in the network.

Comparing the results with those obtained by the classical Hardy Cross technique, an error of 10^{-17} was found.

The main advantage of the presented method is that qualitative information is available. The term values indicate the sense and the degree of the loss pressure influence on the fluid flow rates from the entire network. For example, in order to analyze the influence of the consumer 6, the column 6 from table 1 has to be studied. According to the values from table 1, if the loss pressure parameter M_6 increases, the fluid flow rate q_1 decreases just a little bit and q_4 decreases a lot. The other fluid flow rate value increases should be in the following order: the biggest increase should be noticed at the consumer 4, the second at the consumer 9, next at the consumers 7, then 10, 8, 5, 3, 2, in this order. The values of the corresponding terms from the matrix indicate the decreasing order of the fluid flow variations. Validation was done by solving the system (1) by means of MATHEMATICA software which allows 10^{-15} errors. The differences between the nominal fluid flow rates and the new calculated fluid flow rates are presented in table 2. Indeed, the biggest fluid flow rate is at the consumer 4, then next at the consumer 7, and so one, in the order suggested by the matrix **A**. Without any calculations of the fluid flow rates, only analyzing the magnitude of matrix **A** terms, the fluid flow rates that will increase more or less, when a valve is turning off, can be identified.

According to our knowledge, this type of information is not available by other hydraulic studying methods, so this is the main advantage of using the matrix of influence, instead of classical methods.

4. CONCLUDING REMARKS

The paper presents a method that studies the influence of pressure loss parameters on the fluid flow rates distributed through a radial district heating pipeline network.

The mathematical model synthesizes flow balance equations in the case of a steady state flow. The method considers the network a dynamic and sensitive system, which responds to the variations of input parameters (pressure loss parameters) by variations of output parameter (fluid flow rates).

A numerical simulation was performed into a real district heating secondary circuit, and the analysis of results is presented. The main advantage of this method is that the sign and magnitude of the terms from the matrix of influence indicates how the flows will be reallocated when one of the valves changes the working position; which fluid flow rates from others buildings will decrease and how important that diminishment will be.

Concluding, the method is a useful tool for better flow allocations and for better technical management of radial district heating systems.

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