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DESIGN OF LOW-ENERGY DISTRICT HEATING SYSTEM FOR A SETTLEMENT WITH LOW-ENERGY BUILDINGS

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Abstract

With the integration of new low-energy buildings the traditional district heating (DH) systems with high operating temperatures will have significantly higher heat loss according to the heat supplied to the district. The relatively higher heat loss could be reduced with low operating temperatures of 55 °C and 25 °C in supply and return line of DH network, respectively with a convenient control of in-house installations (substations). Traditional DH pipe dimensioning methods were based on size searching algorithm in which lowest possible pipe diameter was defined according to the limit of max velocity and/or max pressure gradient. Since traditional dimensioning methods cause over-dimensioned network, special attention has to be given to lower the dimensions and as a consequence heat loss from the DH network further. In this investigation pipe dimensioning method of low-energy DH system was developed with an optimization method in the objective of minimizing heat loss from the network while pressure drop values were kept as the constraints through the DH network. In the dimensioning method also descending pipe dimensions were formed in the branched type DH network by taking into account simultaneity of heat load, according to the cumulative consumer load, on each pipe segment separately. According to the traditional dimensioning method, 14% reduction in the heat loss was achieved with the developed optimization method. The resultant pipe dimensions were evaluated via hydraulic and thermal simulation software Termis with simultaneity factor based randomly generated heat demand scenarios for peak winter situation. The simulation results were re-sampled with bootstrapping method and confidence interval of the reliability of the DH system was presented as a result.

Keywords: *low-energy, district heating, pipe dimensioning, simultaneity factor, optimization method*

1. INTRODUCTION

The integration of new low-energy buildings and the low-energy renovation of existing buildings, as a consequence of the efforts to reduce the energy consumption in European buildings, increase the percentage of heat loss from the piping network of a traditional District Heating (DH) system [1-4]. Olsen et al. [5] accentuated that a low-energy DH system operating at very low temperatures, 55 °C in the case of supply and 25 °C of return, can satisfy the heating demand of consumers through an adequate control of the substations [6]. Also, special attention needs to be directed at dimensioning of the DH piping network to prevent over-dimensioned network and high heat loss from the network, which are inevitable consequences of traditional dimensioning methods [7,8]. Descending pipe dimensions were formed in the branched type DH network by taking into account simultaneity of heat consumption, as a function of consumer load, applied on each pipe segment separately [9]. Three pipe dimensioning methods, two of them based on maximum pressure gradient criteria and the other one based on optimization, were compared in terms of heat loss from the DH network [10-14]. The optimal pipe dimensions were evaluated by means of the commercial software Termis with input of randomly generated heat demand data based on simultaneity factor [11,15]. The reliability of the DH network with optimal pipe dimensions was evaluated by use of the hydraulic and thermal simulation software Termis in terms of maximum static pressure obtained through the DH network.

2. ELABORATION

2.1. Methods

In this paper, calculations were carried out separately on each of the pipe segments of which the DH network consisted, as shown at Figure 1.

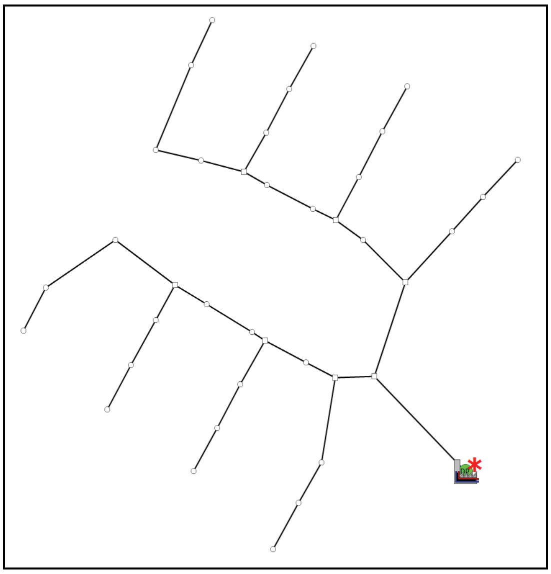

Figure 1. Branched DH piping network as a layout for Trekroner area

2.1.1. Estimation of Heat Load

In this paper, a suburban area of Trekroner (in Roskilde Municipality, Denmark) consisting of 165 low-energy houses with peak heat demand of 2.9 kW for Space Heating (SH) and 3 kW for Domestic Hot Water (DHW) with the use of a substation having a 120 litre buffer tank (more information can be reached at [16-19]), unique for each individual consumer, was studied. A branched type DH piping network was proposed there with total length of 1.2 km trench, excluding end-user connections to the houses. Each consumer in the DH network is not expected to consume heat at full demand level or at exactly the same time, which is the basic idea behind the use of simultaneity factor [9]. Hence special attention was directed at including simultaneity factor at each pipe segment separately as a function of the cumulative number of consumers to which heat is supplied by the pipe segment in question. The heat loads at the pipe segments, including the simultaneity factor as a function of consumer load on them, were calculated in terms of space heating and domestic hot water by use of, respectively, Eq. (1) and Eq. (2) [16,18-20].

$$\dot{Q}_{SHL}(N_i) = \left[0.62 + \frac{0.38}{CC(N_i)}\right] \times CC(N_i) \times \dot{Q}_{SHD} \quad (1)$$

$$\dot{Q}_{DHWL}(N_i) = 1.19 \times CC(N_i) + 1.5 \times CC(N_i)^{0.5} + 0.3 \quad (2)$$

where $CC(N_i)$ is the cumulative consumer number at the node N_i, $\dot{Q}_{SHD}$ is the individual heat demand for each consumer while $\dot{Q}_{SHL}(N_i)$ and $\dot{Q}_{DHWL}(N_i)$ are the heat load for, respectively, space heating and domestic hot water at the node N_i.

2.1.2. Calculations

The pressure drop was calculated by use of the Darcy-Weisbach equation with consideration of the temperature and the flow condition of the heat carrier medium in different pipe segments while the friction coefficient, used in the equation, was calculated by use of Clamond algorithm [21,22].

Heat loss from the DH network was calculated according to the linear temperature dependent thermal coefficient based on the temperatures of the heat carrier medium and ground, distinctively at supply and return lines [3,23,24].

2.1.3. Dimensioning Methods

The heat load defined in chapter 0 was used as an input data for each of the dimensioning methods, given below. Although great reduction was achieved through the lowered heat loads at the pipe segments by including simultaneity factor at each of them, it is still essential to define a proper pipe dimensioning method with special attention given to pressure drop throughout the DH network.

2.1.3.1. Method 1 - The Maximum Pressure Gradient in the Limit of Critical Route

The maximum pressure gradient method in the limit of critical route has been widely used in traditional dimensioning methods. In this method, a critical route is defined with consideration given to the highest pressure drop occurring through the routes, and a maximum pressure gradient value is calculated according to this critical route, which is later used as the maximum limit while dimensioning the rest of the pipe segments in each route at the DH network [10]. In this study critical route was set as the longest route of the DH network. In a fundamental manner, a pump which is dimensioned according to the critical route can also satisfy the lower pressure drops occurring in other routes at a closed loop system [10,21]. The following pipe dimensioning methods, Methods 2 and 3, were proposed according to this fundamental in order to prevent unused potential of head lift supplied by the pump, and as a consequence inevitable over-dimensions resulted by use of Method 1.

2.1.3.2. Method 2 – The Maximum Pressure Gradient in the Limit of Multi-Route

This method is developed on the basis of Method 1. Unlike the limit definition in Method 1, this method allows different maximum pressure gradient limits defined distinctly per each individual route of which the DH network consisted. Each pipe segment thus is dimensioned in the limit of the maximum pressure gradient of the route to which it belonged.

2.1.3.3. Method 3 – The Optimization Method

The excessive unused pressure drop potential, obtained as a result of Method 2, showed that the piping network of DH was still over-dimensioned. On the basis of fundamental, the pump defined for the DH network can satisfy the pressure drop of each route evenly, an optimization method was developed in which the pipe dimensions are reduced until each individual pressure drop through the routes reaches to the maximum allowable pressure drop, with the aim of lowering the heat loss from the DH network. The dimensions of the piping network were determined with simultaneous consideration of objective function - minimizing heat loss from the DH network - and constraint functions - utilization of pressure drops along the routes as much as possible - by means of "Optimization Tool" of the commercial software Matlab with "Active Set" algorithm.

2.1.4. Evaluation of the Pipe Dimensions

The hydraulic and thermal simulation software Termis, in its basic assumption, is based on mass continuity in all of the pipe segments, linked within each other at the DH network. Therefore determination of the heat demands of the nodes, in accordance to the fundamental of the mass continuity, was needed for the evaluation of the optimal pipe dimensions, resulted by use of Method 3, in the commercial software Termis. Several scenarios, representing the peak situation of winter months, were generated as input data for the Termis software by means of randomly generated heat demand data based on use of the simultaneity factors, included in each pipe segment. The results of Termis simulations, such as the maximum static pressure in the DH network and the minimum pressure difference for the consumers, were evaluated in comparison to the design limits defined for them. The purpose of the evaluation was to be sure of the reliability of the dimensions in terms of sufficient pressure drop obtained across the substations of the consumers and maximum static pressure occurring through the whole network, not violating the design limit. The confidence interval for the maximum static pressure was determined by means of the bootstrap method, which increases the reliability of the confidence interval by means of re-sampling the simulation results [25].

2.2. Results and Discussion

Design parameters, given at Table 1, were used as input data to dimension the piping network of the DH system. Maximum allowable pressure drop was calculated as 8 bar for all of the routes of the DH network as a whole for supply and return line per each route. Twin pipes were chosen to be used in pipe selection because of their advantages of lower heat loss and construction cost.

Table 1. Design parameters as input data to dimension the piping network of the DH system

Design Parameters	Set Value	Unit	Description
Supply Temperature	55	ºC	Set on the supply line at the heat source
Return Temperature	25	ºC	Set on the return line at all of the substations
Ground Temperature	2	ºC	Set for the whole DH network
Maximum Static Pressure	10	bar	Set for the whole DH network
Holding Pressure	1.5	bar	Set on the return line at the heat source
Minimum Pressure Difference	0.5	bar	Set for all of the substations

2.2.1. Dimensioning Methods

Figure 2 shows the pressure drop values obtained along the various routes as the results of the three different dimensioning methods in question. The maximum allowable pressure drop was calculated as 1,617 (Pa m^{-1}) for the critical route, defined for Route 8 in Method 1 while as 4,651; 3,520; 2,563; 2,141; 4,643; 3,388; 2,491 and; 1,617 (Pa m^{-1}) for the routes, in order, in Method 2. Both methods resulted in residual unused pressure drop along the routes, which is the main reason for over-dimensioned piping network. Method 3 resulted in pressure drop values obtained as much close to the maximum allowable pressure drop, allowing smaller dimensions for all of the pipe segments at the DH network, as seen at Figure 3. Method 3, due to the optimization algorithm it uses, exceptionally tended to increase the dimensions of the main pipe lines, which hereby allowed further reduction of the dimensions for the street pipe lines. The reduction in heat loss was observed as 2% and 14% by use of, respectively, Method 2 and Method 3 in comparison to Method 1. Although maximum velocity criteria was not considered at Method 3, maximum velocity was reached as 2.4 m s^{-1} through the whole DH network, located at the edge of the street lines.

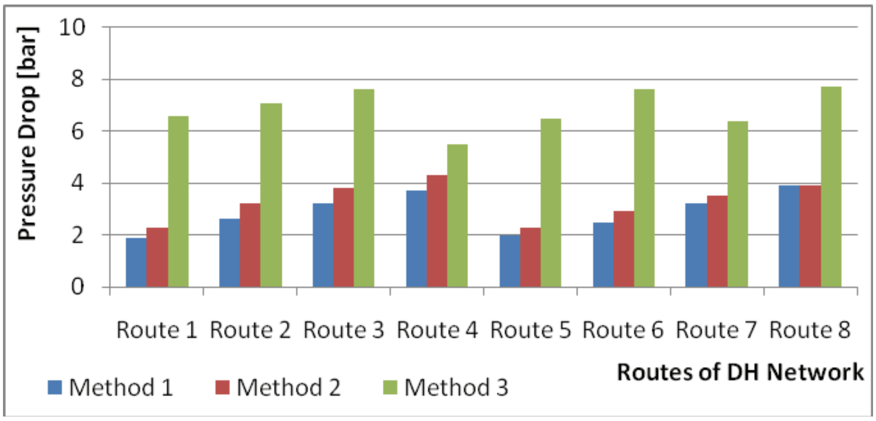

Figure 2. Pressure drop values obtained through the routes as the results of dimensioning methods in question

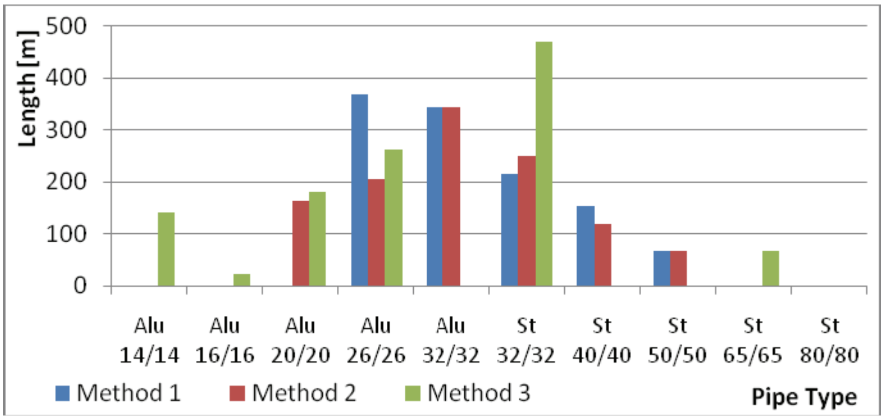

Figure 3. Length of the pipes as a result of dimensioning methods in question (Alu refers to AluFlex Twin Pipe, St refers to Steel Twin Pipe [26]).

2.2.2. Evaluation of Pipe Dimensions

The DH Termis model was simulated hundred times with different individual heat demand patterns, of which the scenarios consisted. The 95% confidence interval of the maximum static pressure, obtained at the DH network, was founded as 1010 ± 3.1 kPa and, after re-sampling the resultant values 50,000 times with bootstrap method, as 1007.5 ± 0.015 kPa. From the confidence interval, it can be seen that the max static pressure values are satisfactory although they are slightly higher than the design limit of static pressure of 10 bar since peak winter conditions occur very seldom, and the pipe segment where observed maximum static pressure was dimensioned with Steel Twin Pipe as a result of Method 3, which has a design limit of maximum operating pressure of 25 bar. Simulation results of the Termis model, with focus given on maximum static pressure, velocity of the flow and pressure difference at substations were shown at Figure 4.

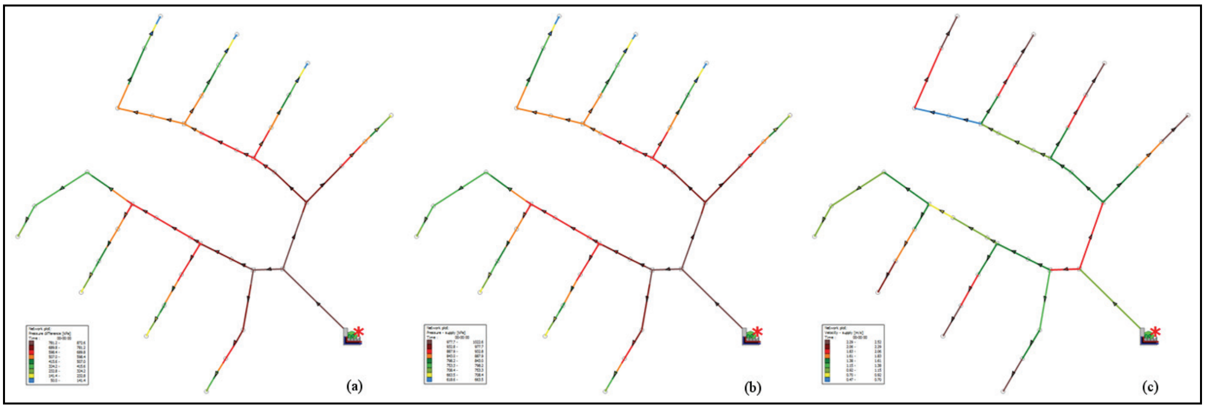

Figure 4. Termis simulation results in respect to (a) Pressure difference (kPa), (b) Static pressure obtained at supply pipe line (kPa) and, (c) Velocity of flow obtained at supply pipe line (m s^{-1})

3. CONCLUSIONS

Traditional dimensioning methods can result in over-dimensioned and as a consequence low energy efficient, DH piping network. Thus in this paper a new pipe-dimensioning method was proposed with consideration given to the aim of reducing heat loss from the DH network while utilizing the head lift provided by the pump as much as possible throughout the whole routes. Special attention was also given to the determination of the heat load by taking into consideration of simultaneity factor at each specific pipe segment, as a function of the consumer number to which each pipe segment supplies heat.

The reliability of the optimal piping network was evaluated by means of simulations which were carried out at the commercial software Termis with the input of heat demand scenarios which were randomly generated by taking into account of the simultaneity factor in each pipe segment. The simulation results proved the validity of the optimization method proposed with 14% reduction in heat loss from the DH network.

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