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Determination of Optimum Network Layout for Low-Energy District Heating Systems with Different Substation Types

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Abstract - *In this paper three different District Heating (DH) network types, which comprise substations with storage tank and with instantaneous heat exchanger (each for domestic hot water production); and booster pumps installed in the beginning section of each street at the latter network type, are pointed out with comparisons given in the point of dimensions and energy efficiency of the DH network. Also, two different network layouts –branched network with bypasses, installed at the end-users, and looped network without bypasses–, which are used to prevent the excessive temperature drop in the supply line during summer months are presented with the focus given to comparison of them in the point of energy efficiency. Results of dynamic simulations, carried out in the Termis software by use of randomly generated heat demand scenarios based on simultaneity factor effect in each pipe segment of the DH network are reported.*

Keywords - District Heating System, Low-Energy, Network Layout, Substation, Dynamic Analyses

1. Introduction

The focus on reducing energy consumption in the buildings as a consequence of energy targets of low energy buildings with implementation of Danish Building Regulations and increased exploitation of renewable energy sources bring the attention to the development of low-energy District Heating (DH) System, which operates with low temperatures such as 55 °C of supply and 25 °C of return [1-3]. As the heat consumption is reduced with the increasing accession of low energy buildings, there is a strict need to plan a heating infrastructure which combines the use of low energy buildings and energy efficient district heating systems based on renewable heat sources [2-7]. The heat loss from the DH network, which will inevitably become relatively high in comparison to the decreased heat demand as a consequence of the pursuance of low energy buildings, can be prevented with low temperature operation [5,8-10]. Concurrently, the potential of renewable heat sources advances due to increased efficiency of heat extraction, thanks to low return temperature [6,10-12]. In addition to the benefits achieved with low temperature operation, special attention has to be given to lower the network dimensions by use of an optimization method which aims to lower the heat loss from the DH network (or investment and operational cost, together) and exploit the head lift provided by the pump at the DH network as much as possible [13,14]. Moreover, concerns have to be given to the substation types of the consumers in order to see the influence on pipe dimensions of the DH network with the purpose of decreasing the heat loss as much as possible. Methods to prevent the excessive temperature drop at the supply line due to low heat demand occurring during the summer months need to be clarified with focus given to energy performance for low-energy district heating systems.

2. Site Description

The district heating network, defined for the suburban area (Trekroner, Denmark), was used to carry out the studies respecting different layouts and types of network. The Trekroner area consists of 165 houses with low-energy standards defined at Be06 software (which later updated to Be10 [15]) with individual consumer peak heat demand values of 3 kW for space heating and for domestic hot water production; 32.3 kW for a substation with heat exchanger or 3 kW for a substation with storage tank of 120 litres (for detailed information: [12,16-19]).
The maximum static pressure for the DH network was defined as 10 bara according to the design static pressure of AluFlex Twin Pipe and the allowable pressure drop through the network was set at 8 bar with a holding pressure of 1.5 bara at the heat source and 0.5 bar allowed pressure difference for each consumer. The ground temperature was defined as 2 °C and 14 °C for peak winter and hot summer situations, at which calculations were carried out [4].

3. Network Types

The heat loss from the DH networks is affected by the dimensions of the pipeline as well as the operational temperature. Therefore the energy performance analyses were evaluated for the branched type (also known as tree formed) DH network (Figure 1) connected to substations with different heat demand characteristics and booster pumps installed at the DH network. The temperature drop through the pipes was assumed to be negligible since there was small change, expected [4,20].

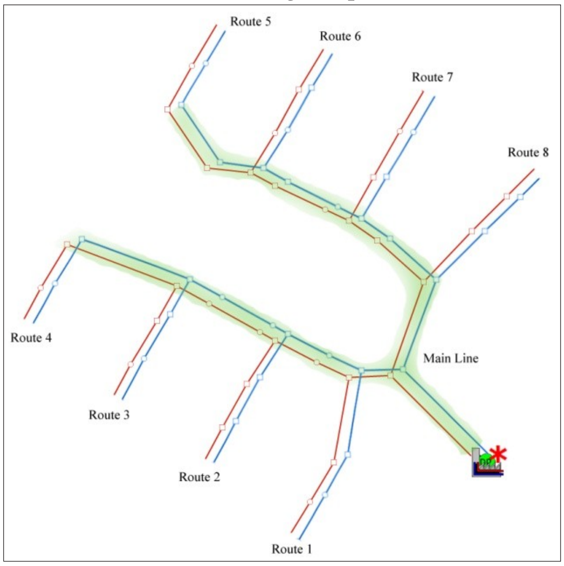

Figure 1. Branched type DH network

Each of the Network Type (NT) was dimensioned with the optimization method [13,14,21-23], which has the aim to minimize the heat loss – as the objective function – while exploiting the head lift provided by the pump throughout the routes as much as possible – as the constraint function – by use of Matlab software with the algorithm of "Active Set". The dimensioning was carried out for the coldest winter condition by use of the peak heat demand data, assumed to be same for all of the consumers [24]. The continuous (not commercially available) pipe dimensions which resulted as the outcome of the optimization method were later rounded up to the commercially available pipe dimensions. Exceptionally, while dimensioning the piping network with NT 3, the constraint function was defined for each route in two parts;

1) from the heat source to the booster pumps
2) from the booster pumps to the end-consumers to which the booster pumps supply heat.

3.1 Network Type 1

In the NT 1, substations at consumers contain storage tanks with a capacity of 120 litres in order to smooth the peak demands occurring during DHW production, with a heat demand of 3 kW for DHW.

3.2 Network Type 2

In the NT 2, substations at consumers contain heat exchangers for instantaneous DHW production upon consumption, with a heat demand of 32.3 kW for DHW production.

3.3 Network Type 3

The possibility of reducing the over-dimension, caused because of the high heat demand at NT 2, was investigated in this network type by use of booster pumps in the DH network in order to increase the head lift through the routes of the DH network (Figure 2). Booster pumps were located in the beginning sections of each street in the area so the main lines (which supply heat to the streets from the heat source to the beginning section of the streets) were dimensioned according to the head lift provided by the main pump located at the heat source, while street lines (which supply heat to the consumers from the beginning section of the streets to the consumer substations) were dimensioned according to the head lift provided by the booster pumps and the residual pressure difference, obtained at the connection point of them with the main line. Although the maximum allowable pressure drop was set to 8 bar for the DH network in the design parameters, the overall pressure drop could be raised to the values higher than 8 bar by the use of booster pumps, allowing further dimension reduction of the DH piping network.

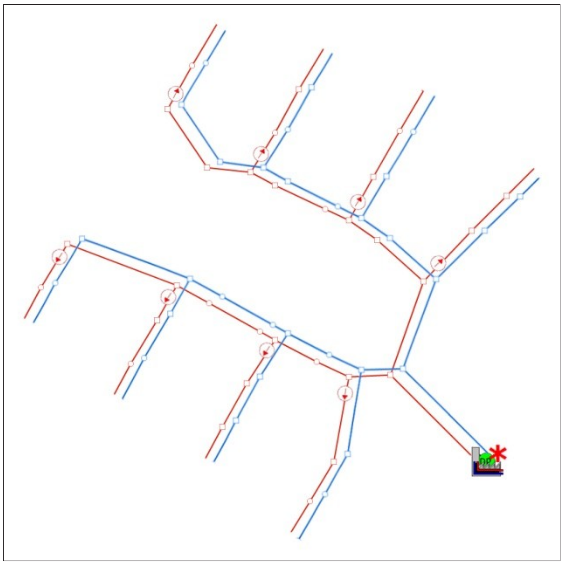

Figure 2. Branched type DH network with booster pumps, installed in the beginning section of each street

4. Network Layouts

During summer months there is no need for space heating, and absence of consumers for holiday purposes decreases the overall heat demand significantly. Decreased heat demand causes stagnant heat carrier medium which stays in the supply line for a long time, which thus causes high heat loss and over-dropped temperatures in the supply to heat demanding consumers [6]. This excessive temperature drop, occurring during summer months, can be avoided by use of two different network layouts.

4.1 Network Layout 1

In this network layout, the excessive temperature drop at the supply line is avoided by use of thermostatic bypasses at the end consumers in a branched type of DH network, which is widely used in traditional DH networks. In cases of temperature drop below a certain temperature, the bypasses at the end consumers direct the supply heat carrier medium to the return line in order to circulate it back to the heat source which supplies heat to the DH network. The mixture of supply heat carrier medium with return medium causes a temperature increase in the return heat carrier medium. Also a high return temperature degrades the efficiency of heat extraction from the heat source [6,25].

4.2 Network Layout 2

This network layout takes advantage of a looped type DH network (Figure 3), which allows excessive connection of consumers to one long (loop formed) pipeline and thus allowing the unused heat carrier medium to naturally circulate in the supply line with the dynamics of the consumptions, i.e. un-consumed heat carrier medium in one particular location at the DH network is circulated in the loop formed supply line to other heat-demanding consumers upon consumption.

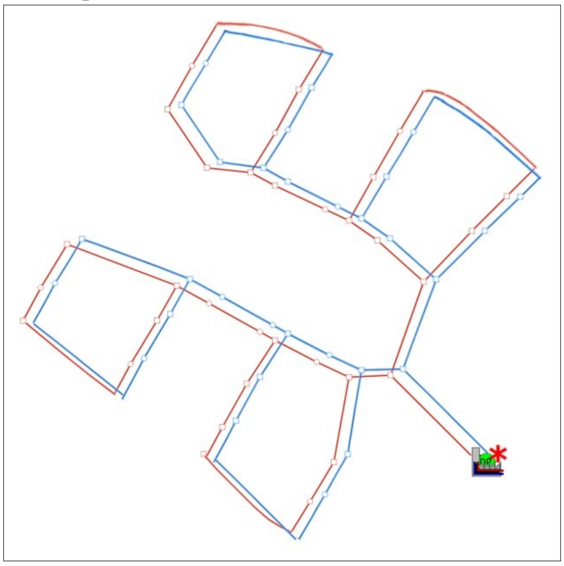

Figure 3. Looped type DH network

Traditionally looped networks are used to increase the security of supply, i.e. in case of maintenance of the pipeline in one side of the looped DH network; heat supply will be provided from the other side of the looped network [26]. However in this paper the looped DH network was used in order to avoid mixing of supply and return heat carrier mediums, which otherwise occur by use of bypasses, and heat loss from the return line. In this paper the looped DH network was formed by linkage of the end-pipelines (of the branched DH network) between each other, and dimensions were defined for these additional pipes by choosing the maximum dimension within the dimensions of the end-pipelines which were linked to each other.

5. Dynamic Analysis of Network Layouts

The heat consumption rates of the consumers affect the operation of the DH network considerably [21,22] and heat consumption depends strictly to the time in a day and also in a year with different characteristic of different magnitudes and duration of the load [27]. Therefore the summer situation of the DH network for both network layouts were simulated with different heat consumption profiles of the consumers in different occupancy[1] ratios representing the summer months. For different scenarios, the occupying consumers' location and their heat consumption profiles were generated randomly in the base of the simultaneity factor effect on each pipe segment in the DH network. Each generated scenario was used as the same input data while defining the heat demands of the consumers for each of the network layouts in order to compare the heat loss and supply temperature, obtained in the results of the simulation.

6. Results and Discussion

6.1 Network Type

Dimensions of the piping network resulted in different variation of the total length of each pipe dimension for different network types, as shown at Figure 4.

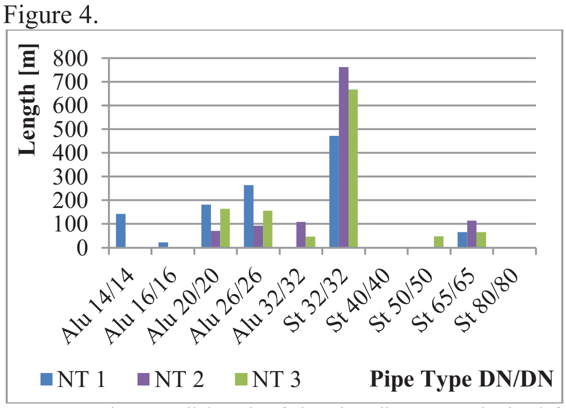

Figure 4. The overall length of the pipe diameters, obtained for each network type[2]

The heat supply, required from the heat source, was calculated as 514 kW and 738 kW in case of connections to substations, respectively, with storage tank (NT 1) and heat exchanger (NT 2 & 3), each for DHW production, for peak winter conditions. DH network of NT 1 resulted in smaller dimensions with 8% reduction in heat loss from the DH network in comparison to NT 2, thanks to great reduction of heat demand by use of storage tank.

[1] Non-occupying consumers were meant to be absent due to holidays.
[2] Alu refers to Aluflex Twin Pipe and St refers to Steel Twin Pipe

The maximum allowable pressure drop values, obtained according to the pipe diameters resulted in NT 3 can be seen at Figure 5.

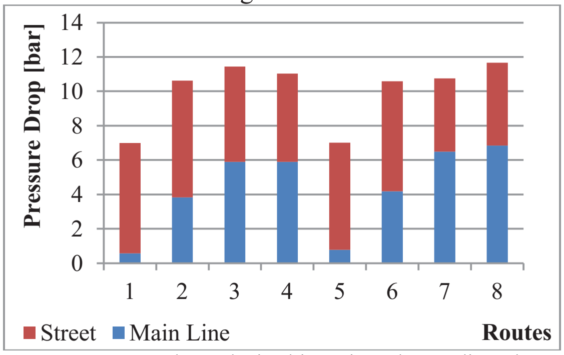

Figure 5. Pressure drop, obtained in main and street lines through the routes

The streets close to the heat source did not need to be assisted with the booster pumps since the existing residual pressure difference (between the supply and return lines) in the main pipeline was already close to the allowable pressure drop limit with values around 7.2 – 7.4 bar. Additional head lift provided by use of booster pumps, each with a capacity of 3.8 bar, in NT 3 resulted in smaller dimensions than NT 2 although the heat demand values were the same for both NTs. However, the reduction in heat loss was obtained as small as 2% by use of booster pumps.

6.2 Network Layouts

The DH network connected to substations with storage tank (with 120 litres - NT 1) was used in the Termis model for both layouts. Five different scenarios were generated for the occupancy ratios of 25%, 50% and, 75% within a time range of 8 hours in 10 minutes time steps. From the Termis simulations it was observed that the rate of heat consumption affect the operation of DH network significantly, mostly in over-low heat demand densities such as occupancy ratio of 25%, as can be seen at Figure 6.

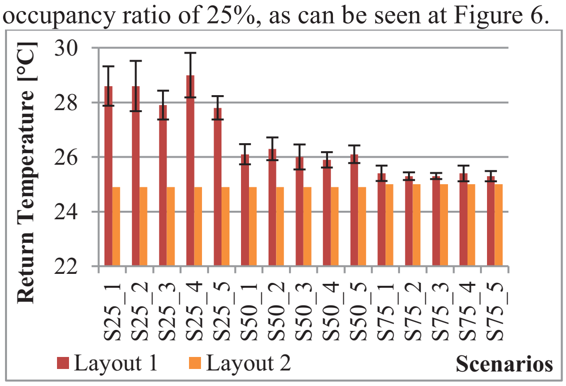

Figure 6. The mean return temperature per each scenario with standard deviation of them, obtained at the heat source

In the figure it can be noted that the return temperature, observed at the heat source, resulted in different variations according to the changing heat demand patterns in the case of Layout 1. Also, it can be seen in Figure 7 that the DH network resulted in larger variation of overall heat loss according to different scenarios at the same low heat demand density in comparison to high densities.

From Figure 6 it can be seen that the occupancy ratio has a significant impact on the magnitude of the return temperature regardless of the minor variations due to different consumer heat demand patterns in the same occupancy ratio at Layout 1, i.e. mean return temperatures were observed from the scenarios as 28.6, 26.1 and, 25.3, respectively for the occupancy ratios of 25%, 50% and, 75%. By the same time, Layout 2 showed a similar behaviour in all of the different heat consumption patterns and occupancy ratios in the point of return temperature same as design value, defined as 25 °C, since no mixture of supply and return was allowed by use of looped network layout.

However, in the point of overall heat loss from the DH network (here the heat loss was represented with heat loss from the DH network over the heat supplied from the heat source – let us say in short as "heat loss/supply") Layout 1 resulted in lower heat loss/supply than Layout 2, as can be seen in Figure 7.

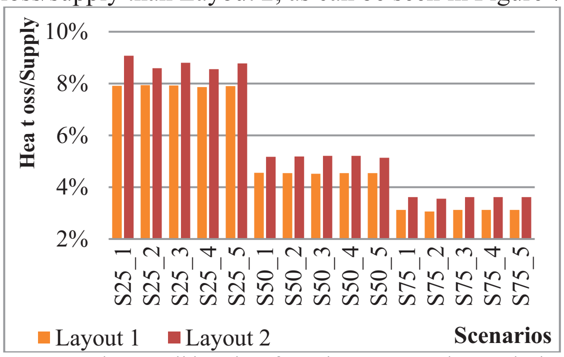

Figure 7. The overall heat loss from the DH network over the heat supplied from the heat source, observed through the whole time range

According to the low changes, obtained in different consumers' heat demand patterns within the same occupancy ratio and according to the significant changes observed with different occupancy ratios, it can be described in general as 'higher waiting time of the heat carrier medium in the DH network (due to low heat consumption) causes more heat loss from the DH network'.

A detailed consideration of a scenario S_{25_3} can be rewarding. Although the same heat consumption patterns were used as input data for the scenario S_{25_3} (Figure 8) for both of the simulations with different layouts, the difference in the variations of the supply temperature can be seen in Figure 9 for Layout 1 and in Figure 10 for Layout 2.

The supply temperature observed at the node K39 reached to low levels such as 37 °C due to lack of heat consumption need from the consumers connected to that node. The node K42 was supplied with supply temperatures as low as 49 °C at Layout 1, while as 38 °C at Layout 2 at the same time step. Both of the situations indicate loss in the heat comfort of the consumers but the duration of low supply temperature occurs in short time ranges.

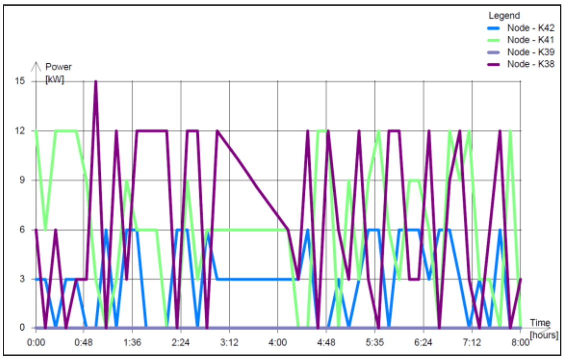

Figure 8. The time series of heat demand power randomly generated in the basis of simultaneity factor for the scenario S_{25_3}[3]

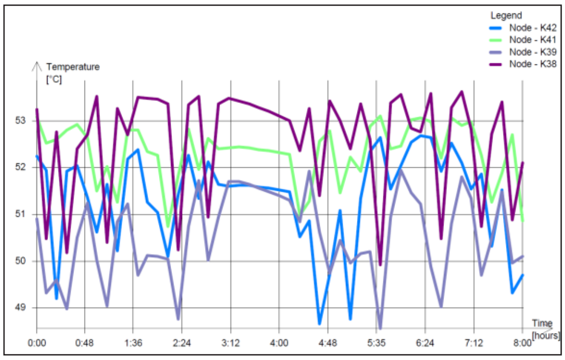

Figure 9. Supply temperatures observed at the end-nodes and predecessor nodes of them in the routes 3 and 4, in case of Layout 1

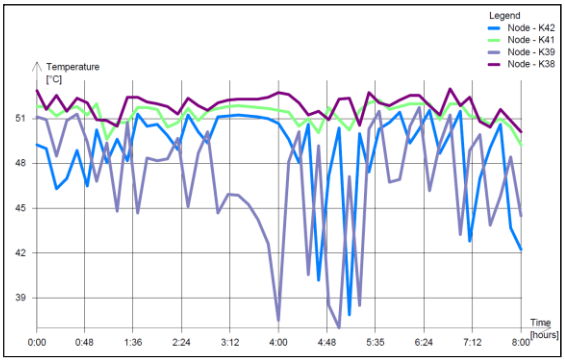

Figure 10. Supply temperatures observed at the end-nodes and predecessor nodes of them in the routes 3 and 4, in case of Layout 2

Although the overall heat loss resulted in various values with higher magnitudes as a result of the simulations based on low occupancy ratios of 25% in comparison to high occupancy ratios, the contribution of the heat loss from the return line was not significant in the overall heat loss from the DH network, thanks to low operation temperature set for return line as low as 25 °C.

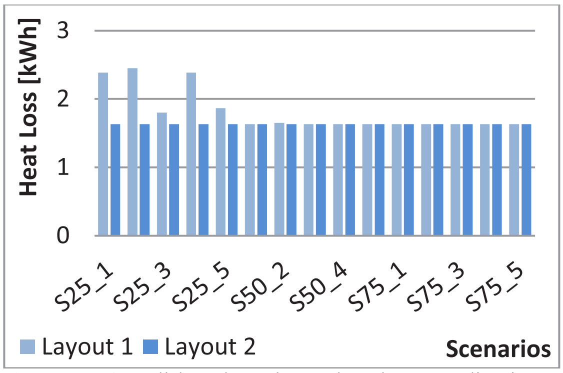

Figure 11. Overall heat loss observed at the return line in each scenario.

7. Conclusions

The paper presented comparisons of different types of substations and network layouts for low-energy district heating systems. According to the analysis, carried out for different substation types, it could be concluded that substations with a storage tank for DHW production result in low piping network dimensions due to reduced heat demand in comparison to the DH networks connected to a heat exchanger for DHW production. Even the booster pumps added at the DH network with connection to substations with heat exchanger, a significant saving was not observed in the point of heat loss from the DH network.

In the network layout analysis, the simulation results showed that the DH network is more sensitive to the heat consumption patterns of the consumers in the situations of low occupancy ratios compared to the high occupancy ratios. Bypasses at the end-node of the DH network allow security of supply temperature around the whole network while a low increase of return temperature was observed at the heat source for extremely low heat demand densities which occur rarely in real life condition. Looped DH network kept the return temperature always close to the design value. However long waiting time of heat carrier medium in the supply line can lead to considerable drops at supply temperature in some particular time steps, which was also the main reason for high heat losses observed at this layout during the simulations.

8. References

[1] H. Lund, Renewable energy systems: the choice and modeling of 100% renewable solutions, Elsevier Science & Technology, MA, USA, 2009, ISBN: 978-0-12-375028-0.

[2] H. Lund, B. Möller, B.V. Mathiesen and A. Dyrelund, "The role of district heating in future renewable energy systems", *Energy*, vol. 35, no. 3, pp. 1381-1390, March 2010.

[3] U. Persson and S. Werner, "Heat distribution and the future competitiveness of district heating", *Applied Energy*, vol. 88, no. 3, pp. 568-576, March 2011.

[4] A. Dalla Rosa, H. Li and S. Svendsen, "Method for optimal design of pipes for low-energy district heating,

[3] K39 is the end-node of the route 3 with node K38 as the predecessor node of it while K42 is the end-node of the route 4 with the node K41 as the predecessor node of it. Since K37 is the predecessor node of K38 without any consumer with heat consumption, it was not included in the simulation results.

with focus on heat losses", *Energy*, vol. 36, no. 5, pp.2407-2018, 2011.
[5] A. Dalla Rosa, H. Li and S. Svendsen, "Steady state heat losses in pre-insulated pipes for low-energy district heating", Proceedings of The 12th International Symposium on District Heating and Cooling, Talinn, Estonia, Sep. 5 - 7, 2010, p. 83.
[6] H. Li, A. Dalla Rosa and S. Svendsen, "Design of low temperature district heating network with supply water recirculation", Proceedings of The 12th International Symposium on District Heating and Cooling, Talinn, Estonia, Sep. 5 - 7, 2010, pp. 73-80.
[7] P. Alberg Østergaard, B.V. Mathiesen, B. Möller and H. Lund, "A renewable energy scenario for Aalborg Municipality based on low-temperature geothermal heat, wind power and biomass", *Energy*, vol. 35, no. 12, pp. 4892-4901, Dec. 2010.
[8] A. Poredos and A. Kitanovski, "Exergy loss as a basis for the price of thermal energy", *Energy Conversion and Management*, vol. 43, no. 16, pp. 2163-2173, Nov. 2002.
[9] K. Çomaklı, B. Yüksel and Ö. Çomaklı, "Evaluation of energy and exergy losses in district heating network", *Applied Thermal Engineering*, vol. 24, no. 7, pp. 1009-1017, May 2004.
[10] P.K. Olsen, H. Lambertsen, R. Hummelshøj, et al., "A new low-temperature district heating system for low-energy buildings", Proceedings of The 11th International Symposium on District Heating and Cooling, Reykjavik, Iceland, Aug. 31 - Sep. 2, 2008.
[11] T. Karlsson and A. Ragnarsson, "Use of Very Low Temperature Geothermal Water in Radiotor Heating Systems", Proceedings of World Geothermal Congress, Firenze, Italy, May 18 - 31, 1995, pp. 2195-2198.
[12] O. Paulsen, J. Fan, S. Furbo and J.E. Thorsen, "Consumer Unit for Low Energy District Heating Net", Proceedings of The 11th International Symposium on District Heating and Cooling, Reykjavik, Iceland, Aug. 31 - Sep. 2, 2008.
[13] H.İ. Tol and S. Svendsen, "Improving the Dimensioning of Piping Networks and Network Layouts in Low-Energy District Heating Systems Connected to Low-Energy Buildings: A case study in Roskilde, Denmark", Unpublished Raw Data, 2011.
[14] H.İ. Tol and S. Svendsen, "Design of low-energy district heating system for a settlement with low-energy buildings", The 3rd International Symposium on Environmental Management towards Sustainable Technologies, Zagreb, Croatia, Oct. 26 - 28, 2011.
[15] "Danish Building Regulation 2010", 2011.
[16] M. Brand, J.E. Thorsen, S. Svendsen and C.H. Christiansen, "A direct heat exchanger unit used for domestic hot water supply in a single-family house supplied by low energy district heating", Proceedings of The 12th International Symposium on District Heating and Cooling, Talinn, Estonia, Sep. 5 - 7, 2010, pp. 60-68.
[17] M. Brand, A. Dalla Rosa and S. Svendsen, "Performance of low temperature district heating systems for low energy houses", International Energy Agency Energy Conversation in Buildings and Community Systems Annex 49, 2010, pp. 174-183.
[18] C.H. Christiansen, J. Worm, H. Jørgensen, J.E. Thorsen, et al., "Demonstration of low energy district heating system for low energy building in Ringgårdens Afd. 34 in Lystrup [Demonstration af lavenergifjernvarme til lavenergibyggeri i boligforeningen Ringgårdens afd. 34 i Lystrup] [in Danish]", Final Report 2011 Maj. Copenhagen: Teknologisk Institut: 2011 Maj. 104 p. Report No.: EUDP 2008-II. Available from: http://www.ibe.dtu.dk/upload/institutter/byg/publications/rapporter/byg-r250.pdf.
[19] C.H. Christiansen, O. Paulsen, B. Bøhm, et al., "Development and demonstration of low-energy district heating for low-energy buildings. Main report and appendices [Udvikling og demonstration af lavenergi-fjernvarme til lavenergibyggeri. Hovedrapport og bilag] [In Danish]", Teknologisk Institut; 2009 March. Report No: EFP 2007. Available from : www.teknologisk.dk/_root/media/34221_EFP%202007.pdf.
[20] H.V. Larsen, H. Pálsson, B. Bøhm and H.F. Ravn, "Aggregated dynamic simulation model of district heating networks", *Energy Conversion and Management*, vol. 43, no. 8, pp. 995-1019, May 2002.
[21] E.H. Mathews, H.F. Brenkman and P.A.J. Köhler, "Optimization of pipe networks using standardized pipes", *R&D Journal*, vol. 10, no. 1- 3, pp. 45-51, July 1994.
[22] A. Benonysson, B. Bøhm and H.F. Ravn, "Operational optimization in a district heating system", *Energy Conversion and Management*, vol. 36, no. 5, pp. 297-314, May 1995.
[23] J. Overgaard and S. Knudsen, "District heating networks - choosing the right pipe dimensions", *DBDH*, 2006.
[24] G. Genon, M.F. Torchio, A. Poggio and M. Poggio, "Energy and environmental assessment of small district heating systems: Global and local effects in two case-studies", *Energy Conversion and Management*, vol. 50, no. 3, pp. 522-529, March 2009.
[25] M. Rämä and K. Sipilä, "Challenges on low heat density district heating network design", Proceedings of The 12th International Symposium on District Heating and Cooling, Talinn, Estonia, Sep. 5 - 7, 2010, pp. 69-72.
[26] R. Langendries, "Low return temperature (LRT) in district heating", *Energy and Buildings*, vol. 12, no. 3, pp. 191-200, Nov. 1988.
[27] H.V. Larsen, B. Bøhm and M. Wigbels, "A comparison of aggregated models for simulation and operational optimization of district heating networks", *Energy Conversion and Management*, vol. 45, no. 7-8, pp. 1119-1139, May 2004.