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DESIGN AND PERFORMANCE ANALYSIS OF A DISTRICT HEATING SYSTEM UTILIZING WASTE HEAT OF A THERMAL POWER PLANT

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ABSTRACT

District heating (DH) systems that utilize waste heat have a great energy saving impact. Based on detailed energetic and exergetic performance analysis of the power plant cycle, it is possible to supply cheaper energy to consumers rather than conventional heating systems meanwhile a small portion of power reduction takes place. In this study, a district heating system, which uses waste heat of a thermal power plant (PP) as energy source is designed and then analyzed for various operational conditions from viewpoint of thermal and hydraulic performance. The implementation site in this study is selected as dwelling estate located at Soma which is in Manisa province of Turkey. Throughout the study, design and analysis of DH system contains several steps: Before all, based on architectural, meteorological and fieldwork studies, peak heat loads are determined for each type of buildings, considering various types of heat transfer factors. Using a software package, network design is carried out numerically. Then a tool is developed to analyze annual heat demand distribution in order to compare estimated and realized data given for 2013-2014 heating season. Lastly, a heat storage tank coupled with existing DH system is dimensioned.

INTRODUCTION

District heating (DH) systems are the networks that carry hot water that is produced in a single or multiple heat centers. Then it distributes hot water along insulated pipes to consumers such as many of houses, businesses, industrial plants and glasshouses. Currently, DH systems are widely used in various places across the worldwide and among these applications, waste heat of thermal power plants (PP) play an important role. For example, as Austria provides about 64% of its district heating demand from recycled systems, Denmark and Poland supply around 70% and even in Romania 91% of the heat requirement dor DH systems from recycled heat [1]. In Turkey, number of DH systems utilizing from sustainable systems like geothermal and thermal PPs are also in increasing manner, currently available in more than 20 districts [2].

Consumers' benefits might be heating, hot water and/or process heat/steam without restrictions of security, discomfort and heating-hot water interruption. DH systems often constitute integrity with sub-segments which are;
Production (i.e. boilers, cogeneration or trigeneration plants)
Transmission and distribution (i.e. insulated pipes, pump stations, primary & secondary heat exchangers)
Consumption (i.e. building sub-stations, hot water storages, instantaneous water heaters, radiators)

District heating systems might utilize from a single boiler geothermal source, bio-fuel plant or waste heat of thermal power plants and factories; which heat source must be adaptable to heat demand by the consumers.

In conventional power plants, especially which are designed only for electricity generation, around 2/3 of fuel energy is wasted through stack gases and cooling water of condensers [3]. This waste energy could be recovered by cogeneration or trigeneration. Cogeneration systems or in other words, combined heat and power plants (CHP) are used for both electricity and heat supply purposes usually utilized from a single energy source. On the other hand, work potential or exergy of these different source types might be various so it is first and vital to obtain the waste energy usability in a thermodynamic cycle. In conventional PPs, work potential of steam decreases through steam generator exit to condenser. Steam could be used for heating purposes rather than mechanical energy production close to condenser. In overall, it can be seen on Figure 1 how exergy increases by recovering heat from PP when steam is extracted correctly. Thus, DH systems usually result in energy saving, which is critical for sustainability.

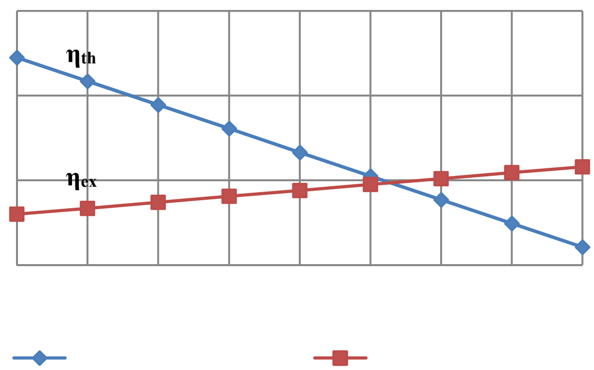

Figure 1 Efficiency vs. Steam extraction rate

Up to now, there were various studies which handled design and performance analysis of district heating systems. However, none of those considered the effects of existence of potential settlement zones.

Heller [4] has studied different types of heat load modeling for the large district heating areas. Dynamic system simulations were presented in the paper, including degree-day data and energy signature models. Accuracy of heat load estimation models was investigated and it was found that degree-day method is the best way to simulate a large system.

Li et al. [5] have investigated the matching rate between heat demand and supply from perspective of energy and exergy performances for a low temperature district heating system. Heat losses were investigated, and ways to overcome these losses were recommended within the paper.

Koiv et al. [6] have researched the financial impacts of dimensioning optimization. Author claims that the real consumptions for district heating applications are two or three times smaller than the estimated values calculated during design process. Results show that boiler, network and pumping costs are reduced significantly as well as the heat loses were reduced. Probabilistic heat load determination method given by author has advantage for dimensioning district heating networks.

Yan et al. [7] demonstrates the energy saving by using distributed variable speed type pumps for circulation loops in a district heating system. Based on Kirchhoff's law and using a resistance ratio, a model was developed to simulate the network. It was obtained that if pump rotational speeds are not synchronous, which means flow rate varies only in one loop, energy saving becomes %71 compared to conventional central circulating pumps. However, if synchronously works, it becomes %31.

One another paper studied by Melino et al. [8] presents a technical-economical optimization procedure in order to reduce consumption and loss by maximizing annual revenue at the same time. In the study, general optimization criteria for design and management were given as investment costs, electrical energy and fuel costs and price of thermal energy. A computer code was developed to analyze pumping consumption and thermal losses. Then a parametric study was carried out to maximize annual revenue.

Lastly, Jie et al. [9] studied on operational optimization model by using a code to reduce pumping and heat loss costs. Minimum operational parameters were aimed to be found using optimization model. It was concluded that by using optimization model, it is possible to minimize effects of losses in heat and electricity. In addition, minimum mass flow rate is limited to frequency range of pumps in real engineering application.

HEAT EXTRACTION & SYSTEM OVERVIEW

Steam Extraction

From viewpoint of work potential, determination of heat extraction location from PP gains more importance in order to keep energetic and exergetic performances at reasonable values. Erdem et al. [3] conducted a comprehensive study to find the best places to extract heat from existing public coal-fired PPs in Turkey. In the study, energetic and exergetic analysis of trigeneration conversion of a public coal-fired power plant was performed. It was found that condenser has the highest waste heat potential of the plant. Another steam extraction point, preheaters have also high waste heat potential. However, these points are not adequate because of their low temperature and capacity or steam extraction might cause substantial decrease in plant performance. It was found that stack gas has low waste heat capacity as well. Thus, analyses revealed that the best point for heat extraction is the cross-over pipe between intermediate and low pressure turbines.

In another study which Soma B Thermal Power Plant is the target PP that supplies waste heat to DH System. Erdem et al. [2] have evaluated energetic and exergetic analyses of the Soma B Thermal PP performed on various points over plant cycle. Simulation results show that exergy substantially increases if steam is extracted from cross-over pipe between intermediate and low pressure steam turbines. In the Soma B PP, steam is extracted from a header which is fed with a branch line taken from cross-over piping and exit line of high pressure turbine. The condensate of steam taken from these points is then discharged into feed water tank. Demineralized water is produced and supplied to the network from water treatment plants of 5th and 6th units. In the end, hot DH water is prepared to be pumped to the district at main pump station. All of following process is the work of district heating design and operation.

By doing such operations, win-win-win comes into place which means all of the operational partners make profit. All of PP company, heat distributor and end-user are able to make profit at the same time.

District Heating System Overview

In this DH system, designated district area is a residential estate mainly consisting of dwelling-houses. The distance from PP to district end-user is approximately 2.4 kilometers. There are a few steps to supply heat to the designated area. First, steam is extracted from main cycle of PP and sent to a heat exchanger to produce hot DH water and then DH water is circulated in the network passing through main pumping and heat station (MPS). In second step, circulating water passes through a heat exchanger at local station located nearby the DH site. There are mainly two zones of heating in the existing DH system. First region consists of potential residence zone of housing which will be included in DH system within near future. Other region, which our study focused, is the demonstration site. Therefore, it is needed to pay attention for this coupled situation while designing the whole system for both demo site and potential zone.

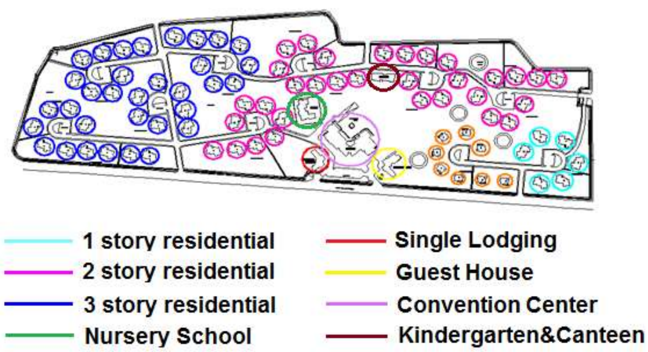

Figure 2 Types and localization of existing buildings within demo site

Within the demo site, there are a few types of buildings consuming heat. 6 one-stories, 32 two-stories, 33 three-stories and 8 duplex residential buildings are present in demo area which yields in total of 346 apartments as in Figure 2. Moreover, 2 mosques, a guest house, a single lodging, a combined building of kindergarten and canteen, a convention center and a nursery school are available as well. Thus, equivalent dwelling number becomes 378 where around 1700 people accommodate daily. In total, 64,971 m^2 gross area in which, 41,158 m^2 corresponds to the heating and cooling area.

Existing DH system was renovated during the project. A central coal-fired boiler was removed and replaced with the new local pumping and heat center. Since new heating method will be based on waste heat recovery from PP, a new transmission line was added to the network. Another renovation was replacement of new well-insulated RTP pipes instead of old network pipes. And the last renovation is the replacement of insulation to the building envelope. Additionally hot water supply is employed with the new renovated concept while it was not available before. Some more additional modifications were also carried out such as new radiators, energy efficient illumination and solar panels for smart grid purposes. For the new renovated concept of the project, main components from main station to end-user are main return pressure boosters with pressure tank, transmission line piping and potential zone distribution network, a brazed plate heat exchanger, a heat storage tank with two circulating pumps, 4 return pressure boosters and a pressure tank for 4 different sub-zones, primary zone distribution network, home entry branch pipes, radiators, valves, counters and sensors respectively. Schematic view is basically given in Figure 3.

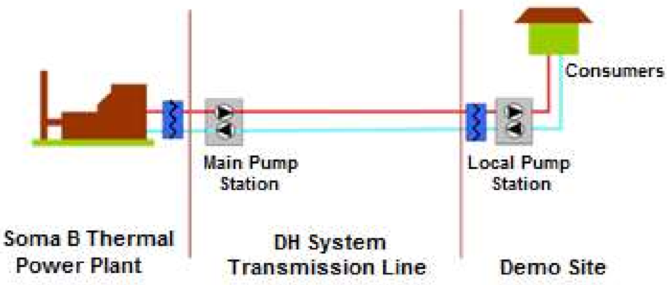

Figure 3 Schematic view of district heating system concept

Before the design process, new structural elements were introduced and their technical data were obtained as a result of the field work in the demo site. Accordingly, U-values of renovated case were obtained and all of the architectural information and drawing of the buildings was determined to calculate heat loads. Based on output of the study, DH system design process was carried out in a similar way to design a central heating system. DH system design and simulation methodology consisted of several steps;

- **Heat Load Determination:** To shape the network, it is first thing to take heat load into consideration. All of further design and simulation process is conducted using this data. Heller et al. [4] have expressed that estimation values for load components are space heating, domestic hot water preparation, distribution losses, additional work-day loads (for businesses) and annual load pattern. It was also expressed that input parameters are ambient temperature, cold-water temperature, solar radiation, wind and humidity in a dynamic simulation manner. Gurses et al. [10] give that input parameters for design are solar radiation, outdoor temperatures, wind speed, number of degree-days, soil temperature and dew point temperature while load components are solar radiation to building envelope, conduction through structural elements to air and soil, infiltration and seasonal deviation. In another reference published by Turkish Mechanical Engineers Chamber [11], there is extensive information related to central heating system design and heat load calculation methods. Most of the utilized correlations in our study were taken from this source which information in that reference book is based on TS 2164 standards. Based on these references and given correlations, a tool was developed to predict heat loads in a software package.

- **Thermal and Hydraulic Design:** To save energy, thermal and hydraulic design of a heating system and its optimization is critical for heating systems. Such big systems that have many components require complicated calculations so that a numerical program to optimize designated network is needed. To overcome this issue, system design and performance analysis was carried out on TERMIS software. Additionally, monitoring and interference detection such as cavitation or temperature unbalance was examined in TERMIS program.
- **Prediction of Hourly Based Annual Heat Distribution:** Based on meteorological data including outdoor temperature and solar radiation, the heat consumption for two years (2013 and 2014) was calculated for both insulated and non-insulated cases. To correlate thermal database and design, a computer code was developed in Visual Basic language. The results of this step were used to calculate annual heat consumption. Calculated results were compared with the real amounts of coal consumption during 2013-2014 heating season.
- **Heat Storage Tank Sizing:** To provide heat supply safety and prevent possible unbalance between heat supply from plant and heat consumption in demo site, a heat storage tank was designed. Here hourly based annual heat distribution and peak heat load was taken as reference for sizing. A code was developed for predicting capacity of heat storage tank.

METHODOLOGY

Heat Load Determination

In Soma District, peak heat load value is calculated utilizing outdoor temperature assumptions for design purposes based on ASHRAE standards as given in [12]. Here, since information is available for city centers only, outdoor design temperature of Soma was calculated by taking average value of surrounding city centers including Manisa, Balikesir, Mugla, Denizli, Aydin and Bursa. The climate, humidity, surrounding geographic shapes and elevation properties of the selected cities have strong similarities with Soma which facilitate us to predict outdoor design temperature as -2.67 °C for Soma town center. Unless given value is calculated with method stated here, it was given in TS 2164 standard as -3 °C.

Another calculation parameter, soil temperature was calculated based on methodology utilizing artificial neural network model developed for Aegean region of Turkey [13]. In Figure 4, scheme of neural network model is given. The input topographic parameters of the code consist of longitude, latitude, elevation, depth in soil and order of the designated month. Figure 5 shows how temperature varies with seasonal progression. The coldest month, January was taken as reference and soil temperature 1 m below the ground, which corresponds to basement level yields 10.08 °C. This value is about 1 ˚C higher than 9 ˚C which given in reference book based on TS 2164 standard **[11]**. It is important to emphasize that unless calculated value is used, heat load would be over predicted.

Wind effects are neglected because the district area is not exposed to continuous wind regime and there is no tall buildings more than 3 floors within the demo site [11]. Therefore convection heat transfer coefficient or h-value of the outer heat interaction could be assumed constant against air velocity. Furthermore the results in reference [4] clarify that wind effects don't have a major influence on heat load determination. Additionally, humidity condition, when latent heat transfer occurs is also neglected because of the low contribution to heat interaction. Thus, effects given above were contained in calculation of sensible transmission with a ratio of %3 [4].

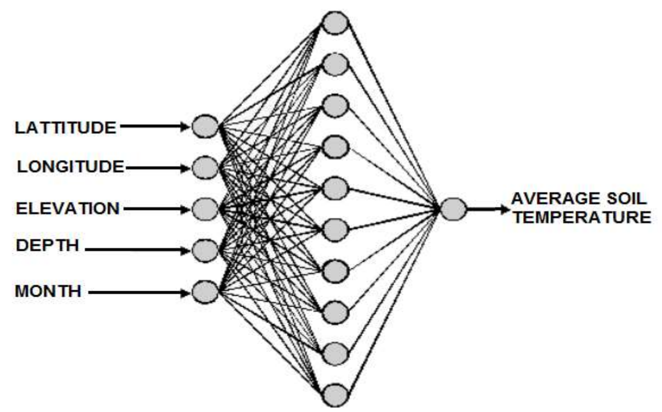

Figure 4 Neural network scheme of soil temperature calculation [8]

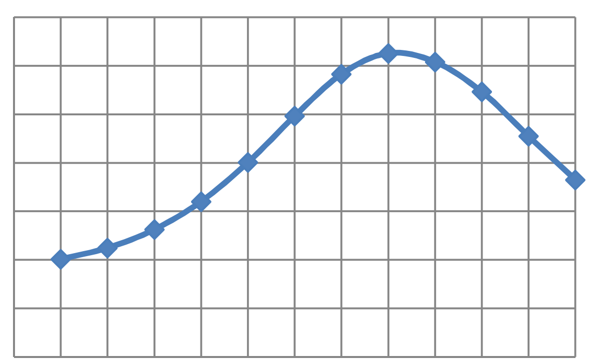

Figure 5 Soil temperature variation during year

On the other hand, solar heat gain was not included into peak heat load calculation to design network and relevant components. This is because the coldest temperatures are reached at night, when there is no solar gain. However, for annual heat distribution, it is needed to take the radiation effects into account. Based on statistical data obtained from Turkish State Meteorological Service, solar heat gain through windows, rather than sensible transmission was calculated with methodology as in equation 1 [14].

$$Q_r = F_c.F_s.q_r.A_g \quad [1]$$

Here, Q_r is the solar heat gain through windows as a unit of watts, whereas F_c is air node correction factor for glass, F_s is shading factor, q_r is solar radiation as a unit of W/m^2 and A_g is the surface area of the glass. Tabulated F_c and F_s factors were available in reference [14]. Other effects are included into the calculation with increase factors as in equation 2 and 3.

$$Q_{increased} = Q_s.Z \quad [2]$$

$$Z = (1 + Z_D\% + Z_H\%) \quad [3]$$

whereas Z_D value is equal to $Z_A + Z_U$ calculated with an overall average heat transfer coefficient (D) calculated as;

$$D = Q_s/A_t.(T_{indoor} - T_{outdoor}) \quad [4]$$

Here, Z_A, Z_U and Z_H coefficients are increase factors that give us opportunity to predict an approximate influence of the following factors; radiation loss from hot inner surface of exterior walls to outer surface, heating interruption, radiation on southern walls due to solar direction (in northern hemisphere) respectively. And A_t is surrounding surface area of a selected room. Given factors are available in reference book [11] based on TS 2164 standard.

In addition to such effects, mass transfer occurs from hotter media to colder ones throughout window and door frame openings, called infiltration which is roughly calculated according to TS 2164 as in equation 5 [11]. This generally occurs when window or door sashes do not overlap to its frame after opened and closed. Also there is interaction between in and out while such components are opened.

$$Q_i = \sum(a.l)_{out}.R.H.\Delta T.Z_e \quad [5]$$

$$R = 1/\left(\Sigma(a.l)_{out}/\Sigma(a.l)_{in} + 1\right) \quad [6]$$

In equation 5 and 6, Qi denotes the heat transfer rate occurred with infiltration while R represents thermal property of the room available in tabulated manner in ref. [11]. Furthermore, H and Ze are also available in tables in ref. [11] based on TS 2164 while "a" is air leakage rate per unit gap of windows and "l" is leakage gap peripheral length. Other than outdoor, indoor temperatures were also taken from comfort standards which are given by TS 2164. Here, temperature for living room and bedroom was taken 22 °C rather than 20 °C given by standards which is more compatible with practical conditions for comfort in active hours of the day [15]. Bathrooms were taken as 24 °C, while kitchens, stairwells and meeting rooms were taken as 20 °C as well. In order to take into account of night cooling, while people in sleep, temperature of each heated room was assumed 18 ˚C from 11.00 pm to 8.00 am for 9 hours. This is because of people don't need such heating during night in practice. Moreover, room comfort temperature is given as 18 ˚C for the nights [15]. This approach is simply different from whole approach which means, in this study, every division of a building is handled separately rather than taking indoor temperature of whole building spaces as 20 °C all the time domain for both hourly and daily basis. Here, it can be inferred that, heat load calculation might be quite different than real values.

$$Q_s = \sum_{i=1}^{I}\sum_{k=1}^{K} U_{ext_i}.A_{ext_{k_i}}.(T_{r_k} - T_o) \quad [7]$$

Here, "k" subscript denotes type of the space such as kitchen, meeting room or bath, whereas "i" denotes type of the façade element enveloping the space such as window or exterior wall. So it is possible to calculate heat interaction of every room individually and dynamically.

Temperatures of non-heated spaces (T_{nh}) such as attic, stairwell and basement are calculated utilizing energy conservation approach with an iterative solution by shooting an initial value of T_{nh} until Q_{out} and Q_{in} gets equal. Here, a code was developed in Visual Basic language. In this way of calculation, temperature of non-heated spaces is computed numerically as well as in a dynamic way for annual approach. Equation 8 explains the way of calculation for iterative solution.

$$Q_{in} = \sum U_{int}.A_{int}.(T_r - T_{nh}) = \sum U_{ext}.A_{ext}.(T_{nh} - T_o) = Q_{out} \quad [8]$$

In equation 7 and 8, U_{int} and A_{int} represents U-values of interior elements such as interior ground or interior wall respectively where "ext" subscript represents exterior elements such as exterior wall, exterior ground, window, door or roof. T_r, T_{nh} and T_o denotes the related temperatures for heated rooms, non-heated spaces and outdoor respectively. Here, building-averaged temperature values of peak heat load conditions for non-heated spaces yield as in Table 1.

Table 1 Comparison of temperatures

Non - Heated Media	Temperature (Tool) (°C)	Temperature (TS 2164) (°C)
Attic (T_a)	16.24	12
Stairwell (T_s)	17.31	15
Basement (T_b)	14.87	12

The last effect of heat requirement is hot water use (Q_h) for daily purposes. The data how much water is used in an apartment is taken from ASHRAE standards and references [16, 17]. The reasons of hot water need might be generation of heat under four categories; small draw-off (washing hands), medium draw-off (dish washing), baths and showers. It is important to note that, hot water of buildings in old system was not utilized from central heating. Thus, while validating developed tool, hot-water use was not included in consideration. However, while dimensioning new system; hot-water use was included in calculations for both peak heat load and annual distribution.

Another factor is that tap water temperature relies on seasonal change as in soil. So, temperature difference in heaters increases in winter, which results more DHW load is required.

While calculating hot water use, diversity factor was also considered for such lumped building sites. Not every individual in the demo site use hot water instantaneously. Instead, a factor is needed to compensate instantaneous effects. During calculation of peak heat load for renovated case, hot water use at peak hours were considered. Peak hot water load was found to be 25 kW_t per flat. Sizing of building substations, instantaneous district hot water (DHW) and network pipes were done with employing hot water use [18, 19].

Furthermore, overall heat transfer coefficient (U-value) of each structural element is calculated for both insulated and non-insulated cases in a previous field work as in equation 9. Sensible transmission of buildings towards outdoor is calculated with the determined U-values. The old structural elements were renovated with new insulation layers as the U-values replaced by new ones as given in Table 2.

$$U = (1/k_t + 1/h_i + 1/h_o)^{-1} \quad [9]$$

Table 2 Calculated u-values of old and renovated cases

Structural Element	Insulated U (W/m²K)	Non-Insulated U (W/m²K)
Exterior Wall	0,42	1,79
Interior Wall	0,4	0,45
Roof	0,2	0,73
Exterior Ground	0,5	2,84
Interior Ground	1,41	1,83
Window	1,2	2,34

In this calculation method, k_t is the thermal conductivity of structural enveloping element which usually consists of several elements. For example, walls consist of brick, plaster and paint, windows and doors consist of double glazed glass and PVC frame, floors include concrete, cement and tile finish and roof constitutes membrane, tile and pitched roof structure and so on. h_i is the convection coefficient of indoor environment which is expected to be constant because of the stable conditions within rooms while h_o the convection coefficient of outdoor environment could be influenced by wind speed. However, since wind effects don't play important role as expressed previously, h_o was taken constant as well.

During calculation of peak heat load, each room was taken independent from each other rather than assuming temperature of whole living space as a constant number. This makes prediction a little more complicated but more accurate. It is important to note that, this might be difficult out of a dwelling-site, for example, on-street buildings, because of the fact that each building has different architectural design. Each room has independently interacted with outdoor, basement, stairwell and attic. A 2D example schematic view of the calculation method is shown in Figure 6.

$$Q_t = \sum_{n=1}^{N}(Q_{s_n} . Z_n + Q_{h_n} + Q_{i_n} - Q_{r_n}) \quad [10]$$

In equation 10, Q_s, Q_h, Q_i, Q_r and Q_t are denoting heat transfer rate with mechanisms of sensible transmission, hot water use, infiltration, radiation (solar heat gain) and total heat demand respectively. And "n" subscript denotes the type of buildings such as two-story dwelling or duplex apartments.

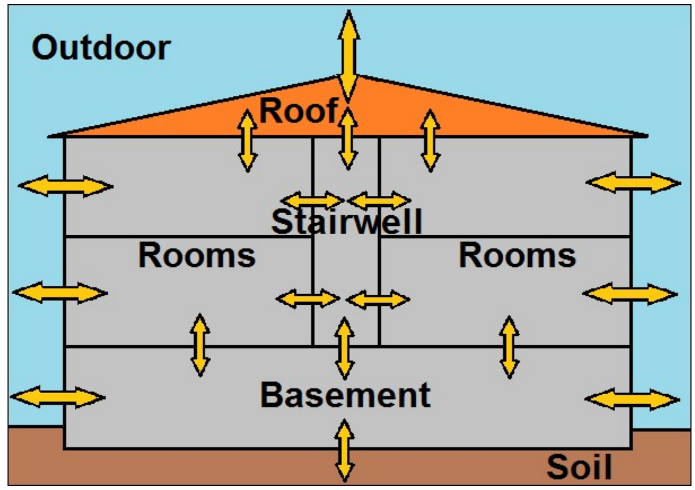

Figure 6 An illustration of calculation method of heat transfer between media

Thermal and Hydraulic Design

When peak heat load is calculated, next step is to design network and selection of equipment. In TERMIS software, it is possible to design and simulate whole network from thermal and hydraulic performance viewpoint. To attain that, input parameters such as district map, elevation distribution, consumption rate of each dwelling and physical properties of working fluid were entered the program in a tabulated manner. After, a database was developed for pipes, pumps, exchangers and plant. Here, pipe database included required physical data such as roughness, internal and external diameter, heat conduction coefficient and insulation material so that pressure gradient, velocity distribution, heat loss and temperature distribution along network could be simulated. Frequency converter pumps were used to attain high energy saving **[7]**. Pump database contained flow rate, head, motor power and characteristic curves related to rotor speed. Thus, system can be simulated under different load factors. Exchanger database included pressure drop, inlet and outlet temperatures at different operating conditions. So, it also facilitates us to predict system behavior at different operational cases.

Based on heat requirement and resulting flow rates, pipe sizing was performed. Except transmission and distribution line, house entry pipes and branches were selected to keep pressure difference and flow velocities under designated values. Then, according to elevation and pressure loss, critical route was determined and then pressure difference between LPS and the differential pressure for critical end user was kept at 100 kPa. Design criteria for DH system are given in Table 3.

Table 3 Design criteria for dh system

*Min. allowable pressure drop in building entry branches:	100	kPa
Max. allowable flow velocity in building entry branches:	1	m/s
Approximate cooling in building substation:	20	˚C
Min. allowable absolute pressure in network pipes:	100	kPa
Temperature inlet to system at main pump station:	80	˚C
Single Loss	1.1	

*: Due to building substation or DHW station

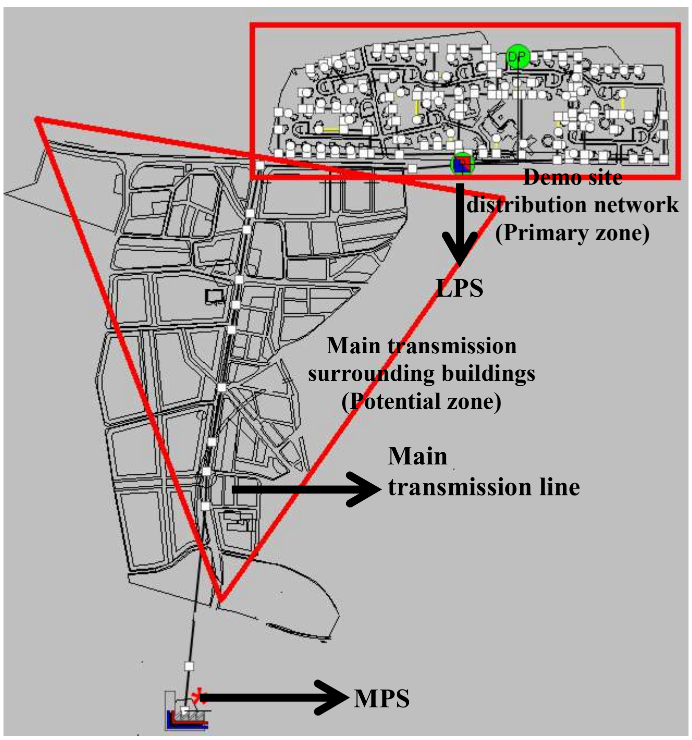

Figure 7 Network overview in termis program

Figure 8 Sub-zones within demo site

In the end of the design process, equipment was determined based on peak heat load. After selection of the equipment in the program, all of sizes were kept constant and off-design analyses were performed. Network location and sub-zone divisions are shown in Figure 7 and 8.

Pressure boosters are located at return side of the transmission line. This is because of equalizing network pressure to expansion tank pressure. Since DH system is divided into 4 sub-zones, 4 pumps circulate hot water for 4 different sub-zones. Another pressure booster, that is located at main transmission line return side at MPS. Here, 6 parallel pumps were used for pressurizing water. All pumps were selected as frequency converter type which facilitates us to work under variable loads and which provides good response to any other change of operating conditions. Head value of the pumps was selected based on combination of pressure gradient through network pipes and cavitation pressure at any designated pressure as in Table 3. Cavitation pressure of water at 80 ˚C is 47 kPa. However minimum pressure along was kept over 100 kPa for safety purposes. Thus, water is pumped to end-user safely.

Pipes are one of the key instruments for DH systems where have importance to supply hot water without cooling. Thus, in this study, RTP (reinforced thermoplastic pipe) pipes were selected which surrounding insulation material is available around the plastic pipe. Thus, it is very effective to transport water to the end-user. Pipes were located under the ground which heat loss depends on seasonal change with soil temperature. In the end, overall heat load is calculated as in equation 11.

$$\dot{Q}_{dh} = Q_t + Q_d \qquad [11]$$

Here, Q_{dh}, Q_t and Q_d denotes overall heat load of DH system, overall heat consumption and distribution losses respectively.

A brazed plate heat exchanger was used at local pump station to transfer heat to the distribution line. Since radiators' designated operational range is between 80 °C and 60 °C, heat exchangers' temperature of cool side was held close to those values. A preliminary economic analysis for 30-year operational case was carried out on different type of brazed plate heat exchangers, and after selection, number of plates was optimized for energy saving approach for pumping. It is also crucial to take into account of temperature of DH side at constant rates at different operational conditions. Response of heat exchanger for these conditions was examined as well.

When overall heat load is determined, heat load for non-renovated case was compared with lignite consumption rate within 2013-2014 heating season in order to validate the given assumptions and methodology. The comparison is performed with total energy output extracted from burned lignite in the old boiler. The energy output was calculated as in equation 12.

$$Q_c = \eta_{boiler} . H_u . m_{coal} \qquad [12]$$

In the given equation, m_{coal} is the lignite burned during 2013-2014 heating season while H_u denotes the lower heating value of the lignite utilized in the burner and η_{boiler} denotes the thermal efficiency of the coal boiler.

Hourly Based Annual Heat Distribution

Before all, two-year (2013-2014) statistical data of 17520 hours for air temperature and solar radiation of Soma town center were obtained from a public institution and adapted into the tool that was previously prepared for heat load prediction. Within this approach, dynamic simulation of the demo site was conducted. Here, dependent variables in this step are outdoor temperature (hourly basis) heated room temperatures (hourly basis), soil temperature (monthly basis), hot water use (both hourly and monthly basis) and solar radiation (hourly basis).

After two-year simulation was completed, total heat consumption rate of the DH site was calculated. This is important for analyzing heat supply-demand balance and economic impacts over seasonal variation by the PP. In addition to that, individual influence of heat load factors was analyzed such as solar heat gain or infiltration. So, there could be some further modification on buildings in order to reduce heat loads. For example, if heat loss in pipes occupies an important area within total heat load, a modification in pipes or inner flow could help to enhance the transmission efficiency in DH network. If infiltration is too high, window frames could be modified with newer ones. So, it could be said that, before and after design process of a DH system, dynamic simulation might enable us to monitor performance effects.

In Figure 14 and Figure 15 annual heat load distribution values could be seen for two-year domain including heat loss through pipes. Here, distribution losses were also taken into account in a dynamic viewpoint. Since loses depends on temperature difference between inside and outside of the pipe and also depends on that pipes are under the ground as well. Thus, to attain a dynamic approach, loss factors were calculated varying with soil temperature.

Based on TERMIS design, overall heat load for 2013-2014 heating season was compared with lignite consumption of the demo site took place within that season.

Heat Storage Tank Preliminary Sizing

Heat storage (HS) systems are usually used as coupled with a DH system in order to optimize finances in accordance with PP operation. Heat storage tank could be charged when electricity sale prices are low, and discharged when it is high. So PP can focus on only electricity generation when sale prices are high enough. Thus, PPs can do a financial optimization in order to increase profits. One another reason for using heat storage tanks is to compensate possible power interruptions occurred by PP. By doing so, heat can be supplied to the end-user without any uncomfortable situation **[20].** In this study, heat storage tank is used for power compensation.

In order to adapt an efficient discharge, physical background of the tank was selected as thermally stratified. This means there is a significant temperature difference between upper and lower region of the tank volume. Stratification could be carried out with diffusers that are placed top and bottom of the tank. When hot water to be pumped to district, water is discharged from upper side of the tank where storage media is hot enough. Additionally, tank geometry was selected as cylindrical to reduce heat transfer rate which depends on proportion of surface area to tank volume.

To design a HS tank, first step is to calculate capacity of the tank. Tank capacity (Q-value) is calculated with peak supply energy without interruption, which means summation of heat load difference with average supply, during a discharge phase without any charge. Based on annual data, it is easy to determine when this situation takes place. Generated code in Visual Basic language also gives what tank thermal capacity should be.

HS systems are working based on supply-demand balance. Usually if overall heat load is more than rated energy supply by the PP, pumps start and discharge hot water from storage tank. Otherwise, return pumps charge the tank. This daily procedure could help to optimize heat-demand balance.

When HS tank is being sized, tank geometry is determined to be cylindrical in which H/D ratio is around 1.5 where H denotes height and D denotes diameter of the cylinder. This is because of to maximize discharge efficiency. **[21]** For a preliminary approach, H/D ratio is set equal to 1.5. Another dimension, inlet/outlet pipe diameters are also calculated according to flow rate calculated by peak heat load designated flow rate. In equation 12 and 13 calculation of the tank size is given.

$$t_{ch/dch} = Q/\dot{Q}_{dh} \quad [13]$$

$$V_{tank} = t_{ch/dch}.\dot{V}_{dh} \quad [14]$$

Here, Q is the thermal capacity of the tank whereas $\dot{Q}_{dh}$, V_{tank}, $t_{ch/dch}$ and $\dot{V}_{dh}$ are denoting the discharge power, tank volume, charge/discharge duration and volumetric flow rate of the HS tank to the DH system.

However, for full design, numerical and experimental studies must be conducted in order to optimize discharge efficiency, which could be further studied.

In our study, heat generation and supply by the power plant is set to a value that is average heat load along a designated day of the year. If heat load goes over the average value, charge is performed. If not so, discharge is done from HS tank.

RESULTS AND DISCUSSION

In the DH system studied, peak heat demand by the demo site was calculated as 1655.2 kW_t since this value was 4032.4 kW_t before renovation for non-insulated buildings. Thus, peak heating demand has been reduced approximately % 59 by implementing renovation, which means lower size and lower capacity of equipment is enough. After performing thermal & hydraulic analysis with old pipes and addition of distribution losses, overall heating load became 1773.1 kW_t and 4176.8 kW_t

for renovated and non-renovated case, respectively. One point is important at this step. While performing thermal & hydraulic design for renovated case at peak heat load, peak hot water use has to be included. With this information, peak heat consumption for demo site becomes 2905 kW_t instead of 1655.2 kW_t.

The predicted heating demand value in the tool slightly differs from the calculation method with assumptions given by TS 2164. When applying those assumptions into the tool, the value for renovated case became 1550.6 kW_t which underpredicts around % 7 as compared to given methodology and became 4068 kW_t for non-renovated case which overpredicts the value around % 1. The deviation rate differs for two cases. This is because of non-heated space temperatures in assumptions given by TS 2164 were taken same for both renovated and non-renovated cases, which actually should have been calculated according to operating conditions. In dynamic approach, given assumptions might cause serious errors. However, in TS 2164, it is also explained that given assumptions don't give accuracy, non-heated spaces should be calculated separately. **[11]** The results are shown in Figure 9.

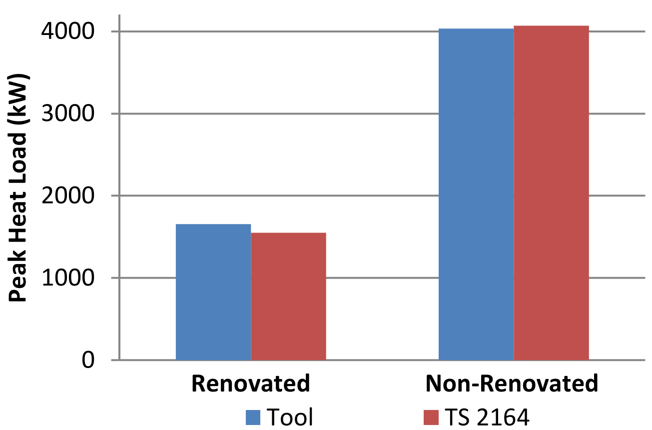

Figure 9 Calculated space heating loads

While performing dynamic simulation, distribution loss factor was introduced for different loading conditions. To attain that, soil temperature was averaged based on seasonal change for each load factor. In TERMIS, load factors varying from 1.0 to 0.05 was simulated and loss factors were computed based on loading. Thus, loss factors were found corresponding to each loading factor. Loss factors were multiplied with the heat demand for each designated condition. The results yield the overall heat load. The loss factors varying with load factors are shown in Figure 10. Loss factors are also required to perform dynamic simulation. Following that, to analyze annual performance of the DH system and selected equipment, a full dynamic simulation was performed for two years. (2013-2014). Figure 14 and Figure 15 show how loading values vary annually.

In order to validate the methodology explained in this paper, energy output based on lignite consumption amount for 2013-2014 heating season was compared with the predicted amount of energy consumption given by the tool. Since H_u of the lignite is 4594 kcal/kg which is equal to 5343 kWh/kg, mass of the burned coal in the boiler is 2825.3 tons and thermal efficiency of the boiler is approximately 0.6. From the given data, energy extracted from lignite yields 9057 MWh where predicted value based on annual dynamic simulation became 8988 MWh. Thus, the deviation between two values becomes % 0.7 only, which means our prediction with given methodology has a very good agreement with the real value realized in the demo site. In Table 4, predicted amount and real consumption value based on lignite combustion is given.

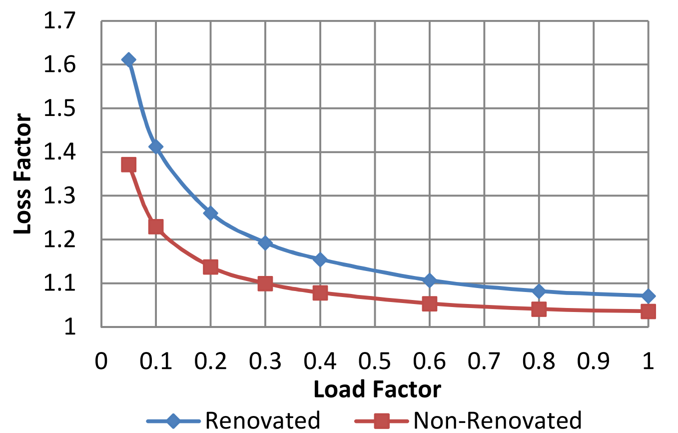

Figure 10 Load factor vs. Loss factor

When computing heating demand and overall heating load, heat values varied for renovated and non-renovated cases. In order to detect where of the DH system has majority of the losses, this important to carry out further modifications. The heat load values are given in Figure 11 and Figure 12.

Table 4 Predicted heat load vs. Real consumption for 2013-2014 heating season

	Heat Load (MWh)	Deviation (%)
Predicted (Q_{dh})	8988.17	-0.7
Real (Q_c)	9057.35	

Based on annual heat load distribution, solar heat gain through windows and hot water use were kept constant as independent from renovation. With modification in enveloping building surface, sensible transmission was directly affected and other losses and distribution losses were also changed with sensible transmission.

Before renovation, annual sensible transmission was 6315 MWh and other losses were 445 MWh while distribution loss was 948 MWh and infiltration was 1399 MWh. After renovation, 6315 MWh of sensible transmission has reduced 2443 MWh, 1399 MWh of infiltration has reduced down to

1006 MWh, while 445 MWh of other losses have reduced to 171 MWh. On the other hand, for both of cases, solar heat gain was determined around 106 MWh. Conversely, 948 MWh of distribution loss increased up to 1057 MWh because of the employment of hot water use. Hot water use for renovated case became 6181 MWh.

By given annual data, overall heating consumption was used to be 8988 MWh, after renovation, the value became 4760 MWh when excluded hot water use. Thus, annual energy saving became %47 for 2013-2014 heating season. When included hot water, heat consumption value became 10583 MWh.

Furthermore, HS tank preliminary sizing was carried out information obtained from annual simulation. At this step, heat consumption of renovated case was taken into account. After simulation, tank capacity was found to be 6951 kWh and discharge power at peak heat load was previously determined as 2905 kW_t.

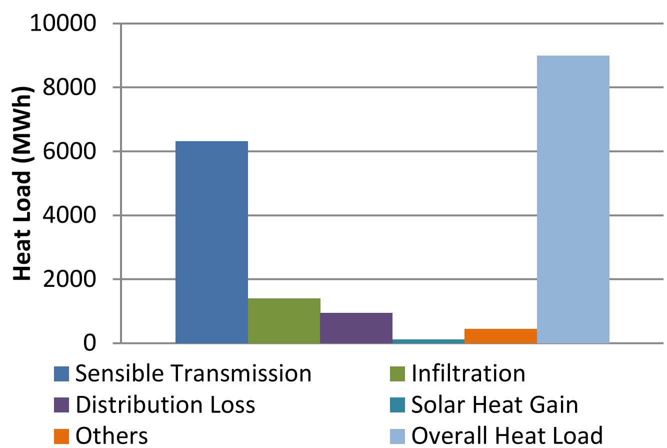

Figure 11 Annual heat load distribution over heat consumption mechanisms – before renovation

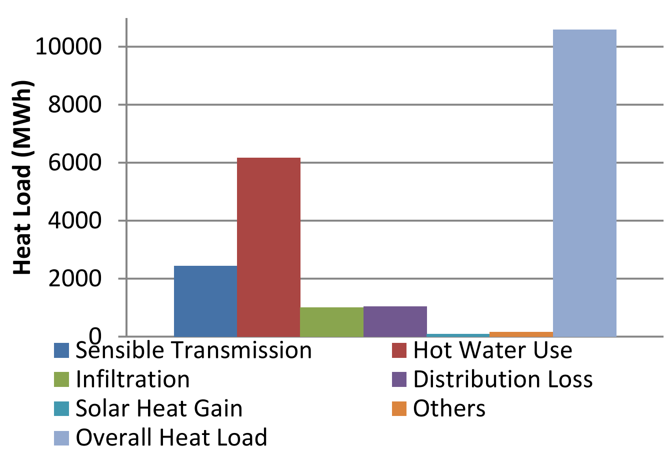

Figure 12 Annual heat load distribution over heat consumption mechanisms – after renovation

HS system could supply water to demo site for around 2 hours and 15 minutes at peak heat conditions. Water flow rate at this power approximately 35 kg/s and thus, tank volume was found to be 325 m^3. While thinking of H/D ratio to be 1.5, height and diameter of the tank was calculated as 9.6 and 6.8 meters respectively. Reference day for tank capacity was found out to be 6th January of 2013 when maximum capacity of a heat discharge period is reached. The day and discharge energy distribution are shown in Figure 13. However, it is important to remember these dimensions are only for preliminary approach. Further experimental or numerical study is required to be conducted to find optimum sizes of heat storage tank.

As seen on Figure 14, heat load distribution was analyzed for two years beginning from 1st January of 2013 to 31st December of 2014. Peak heat load of 2905 kW_t is rarely reached during this period. While outdoor design conditions are being calculated, statistical data of long years such as 30 years of climatic database is used.

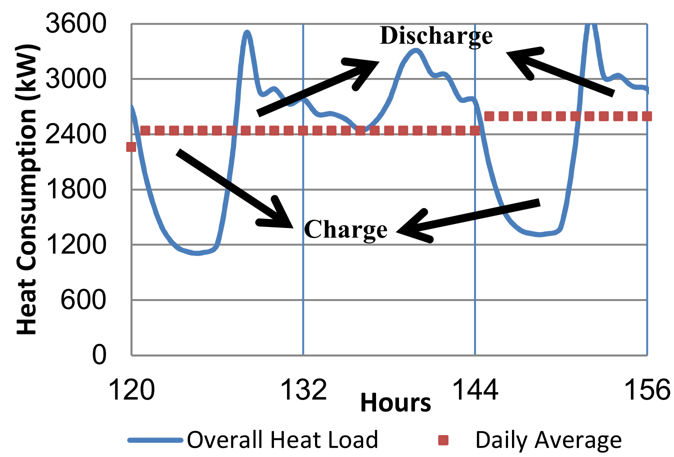

Figure 13 Schematic heat storage tank capacity determination

As explained before, demo site was separated into 4 sub-zones. Zone 4 is the critical zone, which has the minimum pressure difference in the end-user., where the furthest end-user has minimum differential pressure set at 100 kPa. Any other end-user in the demo site is to be over 100 kPa.

Additionally, lowest network pressure was found within Zone 2 which is slightly over 100 kPa whereas lowest pressure within Zone 4 was found to be around 170 kPa, as given by design criteria in Table 3. In Table 5, thermal & hydraulic properties of end-users of each separated sub-zones are seen.

Differential pressure is needed to give as input in buildings. Because radiator cores, DHW stations or building substations have pressure loss which varies with flow rate, however, usually kept around 100 kPa at full flow rate for our buildings.

After design and simulation, performance of the whole DH system was analyzed in TERMIS software. Pressure and temperature distribution was analyzed for various cases. Demo site, including transmission line, was analyzed for different load factors and numerous inlet temperatures.

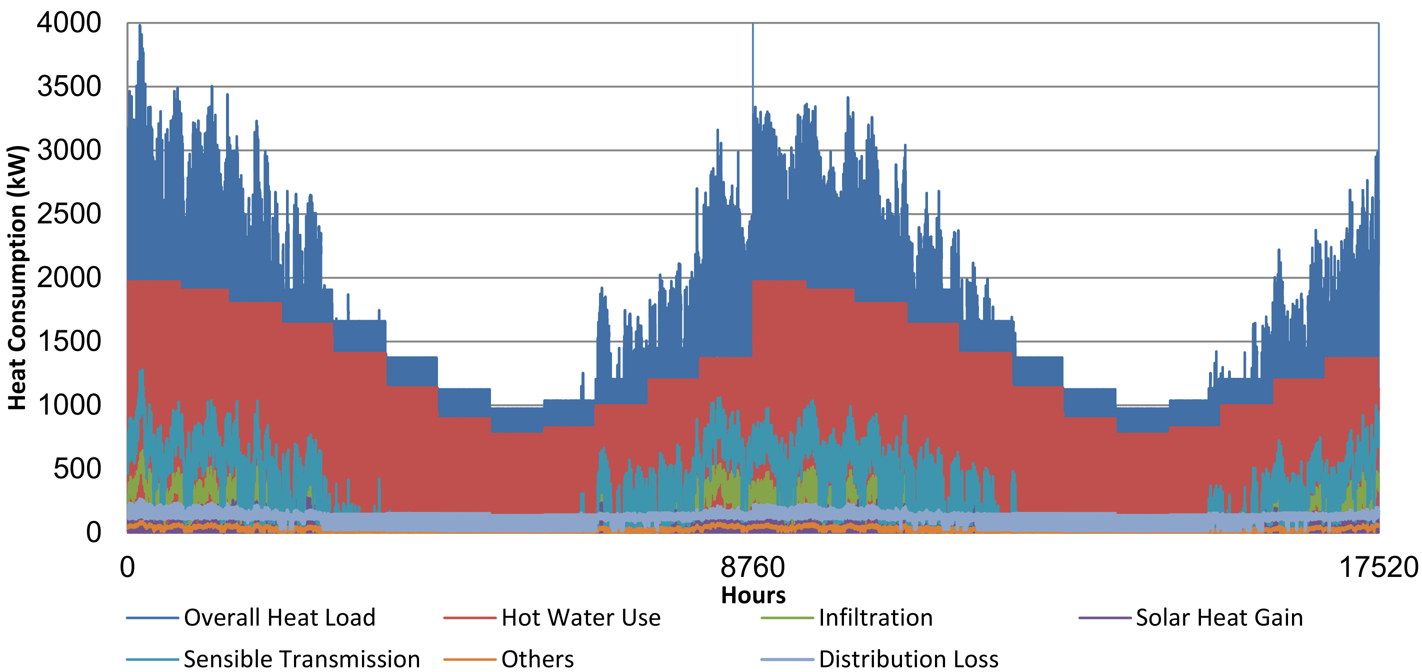

Figure 14 Two-year annual heat load distribution with different loading conditions

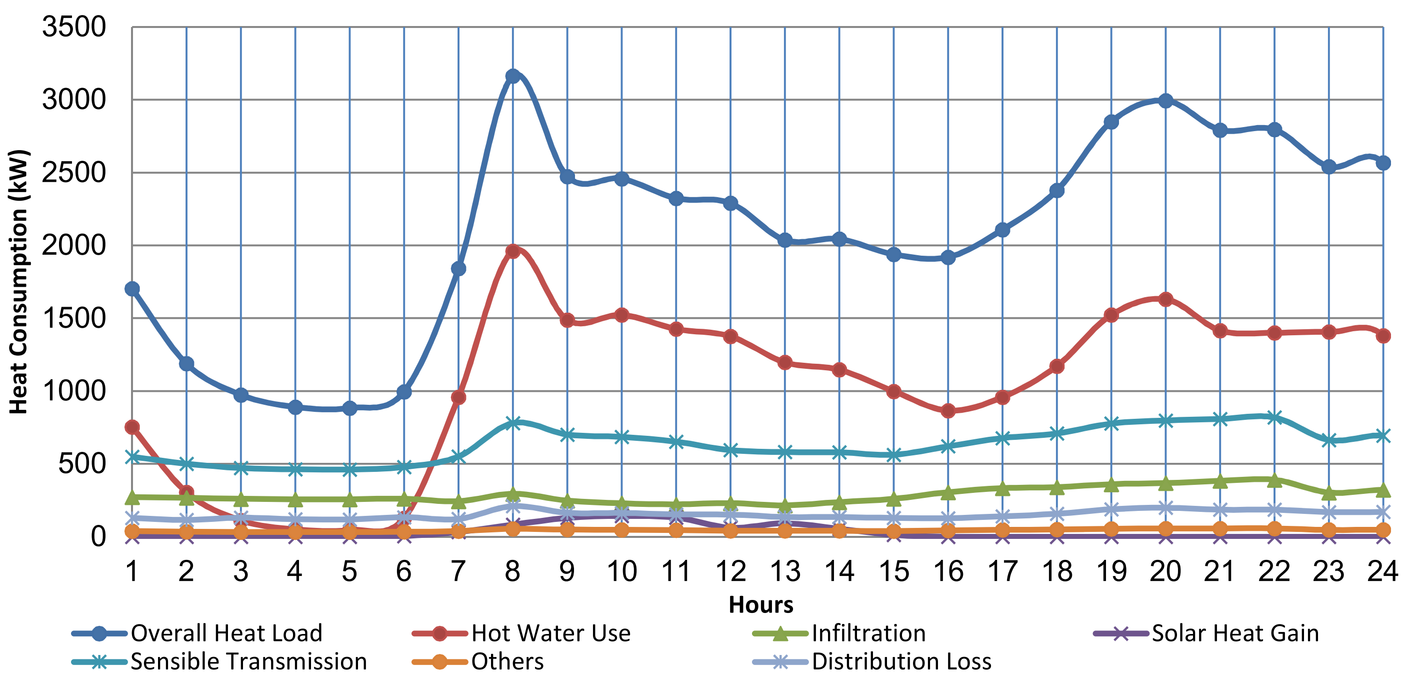

Figure 15 Heat load distribution for an example day (1st january 2013)

On the other hand, system was also analyzed for coupled settlement including potential zone located backward of the demo site. Figures 16, 17, 18, 19 and 20 shows how DH system response is. During analysis, exchanger temperatures and pressure losses were adapted to different operational conditions. In Figure 16 and Figure 17, pressure analysis was completed for various cases. In Figure 16, as stated before, DH system was analyzed as coupled with potential zone. In other words, future simulation was performed. When demo site is divided, minimum pressure along network move away to 300 kPa. However, when potential zone is coupled, minimum pressure value gets closer to 100 kPa which is minimum allowable pressure. It is important to note that, because of the fact that additional pressure losses are being existed in the dwellings within potential zone. If potential zone was not considered during design, there would be hydraulic problems such as cavitation along network.

In both cases, pressure boosters take pressure values to reference expansion tank pressure. Another point is that, in return side of transmission line, pressure is first decreased and then getting greater as it move close to main pump station. This is of course because of elevation variation along the network. In Figure 17, different load factors were analyzed for divided case. It was an expected result that, mean pressure values increase as load factor reduced. Less flow rate means less velocity within pipes. Thus, pressure losses decrease along the network.

In Figure 18 and Figure 19, temperature analysis was conducted based on design in TERMIS. In Figure 18, coupled and separated cases were analyzed. Here, the most outstanding condition is that, return water in distribution side getting hotter as it moves to main pump station. This is because of buildings in potential zone having average temperature more than houses in demo site. Thus, return water is getting hot when return water of building joined to water along main transmission line.

As shown in Figure 10, load factor has controversial relation with loss factor. As load factor is getting higher, heat loss factor gets smaller. In Figure 19, as load factor reduces, losses increase and mean temperatures are also being decreased because of there is less heat loss. Thus, heating water to end-user becomes smaller when load factor is low. As loss factor has an exponential variation, temperature divergence is also exponential. In Figure 19, it is obvious that for low load factors, house inlet temperature becomes much lower than the case as in high load factors. This might be bothersome in summer season. However, as the house inlet temperature is still around 60 ˚C, there won't be any bothering condition. Therefore, it should be dynamically monitored how much heat loss occurs along network pipes. It should also be considered that, if water is pumped as approximately 60 ˚C from MPS, inlet temperature mean pressure values decrease when system is coupled, at end-user would be around 40 ˚C. This value is not useful to heat a room because of low energy capacity. Therefore, plant operation should also be carefully performed.

In Figure 20, different temperature conditions were analyzed unless inlet temperature in MPS is 80 ˚C. It is seen on the figure that, when MPS inlet temperature is 70 ˚C, house entry temperature reduces to about 65 ˚C. It is expected that in warmer season, if load factor is equal to or lower than 0.1, house entry temperature would reduce down to 52 ˚C which might be critical inlet value for radiator cores in the dwellings. When temperature difference between heating fluid and heated media becomes smaller, performance of the DH system reduces as well. Therefore, it is important to keep plant extraction temperature over certain values.

In general, the results in this paper show that DH system responds to design well. Hydraulic performance is good whereas there is no cavitation risk, excessive pressure losses or critical pressure differences. At different loads, frequency converter pressure boosters help to maintain system performance. Thermal performance was also well along the network. However, it is important to monitor system performance permanently. For a DH system utilizing waste heat, heat source is also critical which means plant operation is crucial. Temperature at MPS must not be lower than certain values.

Table 5 Properties of end-users for each sub-zone (load factor: 1)

	Supply Pressure (kPa)	Return Pressure (kPa)	Lowest Pressure* (kPa)	Inlet Temp. (˚C)	Outlet Temp. (˚C)
Zone1	281.6	152.8	142.1	74.6	54.6
Zone2	301.6	163.8	154.7	74.4	54.4
Zone3	322.8	181.9	162.4	73.2	53.2
Zone4	318.2	218.2	187.4	74.1	54.1

*: Lowest pressure along network

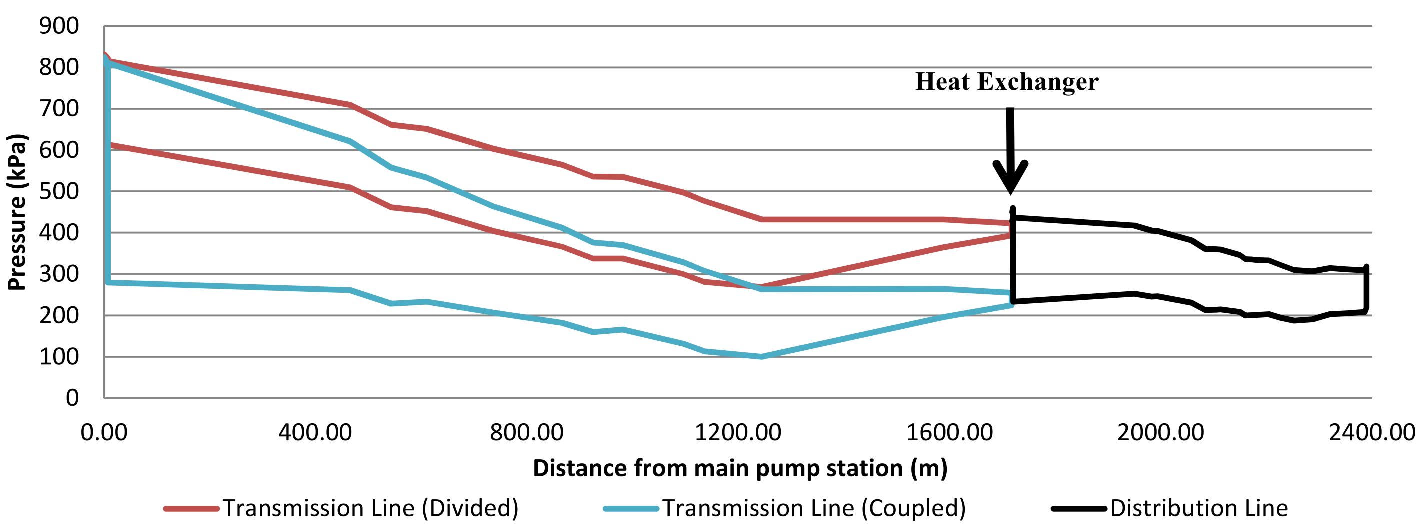

Figure 16 Pressure variation of dh system at full load – divided and coupled

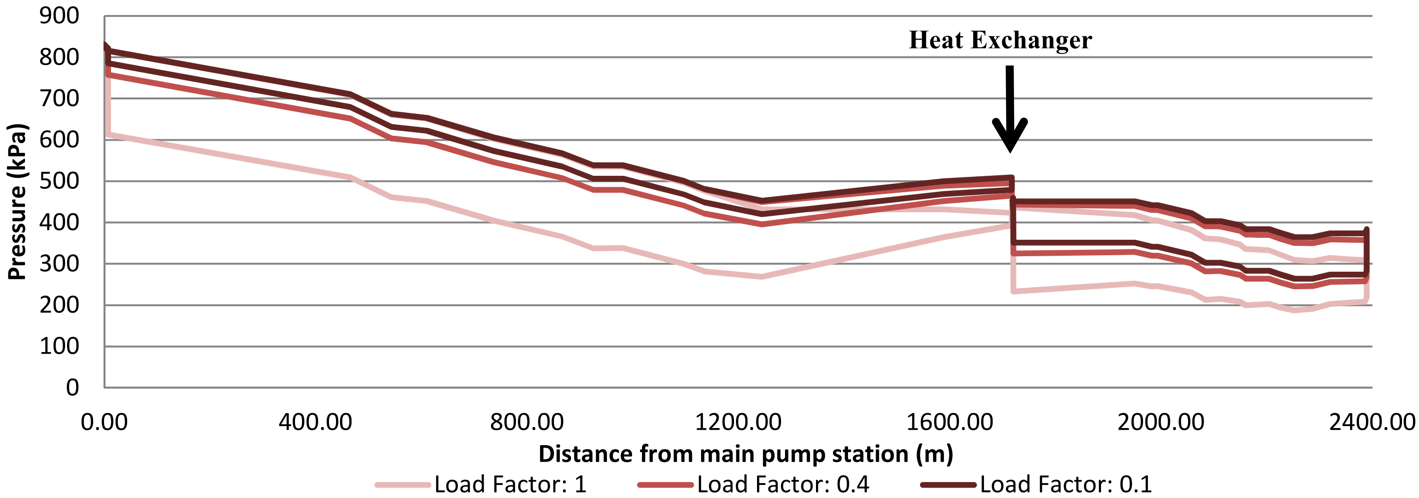

Figure 17: pressure distribution of dh system with different loading factors - divided

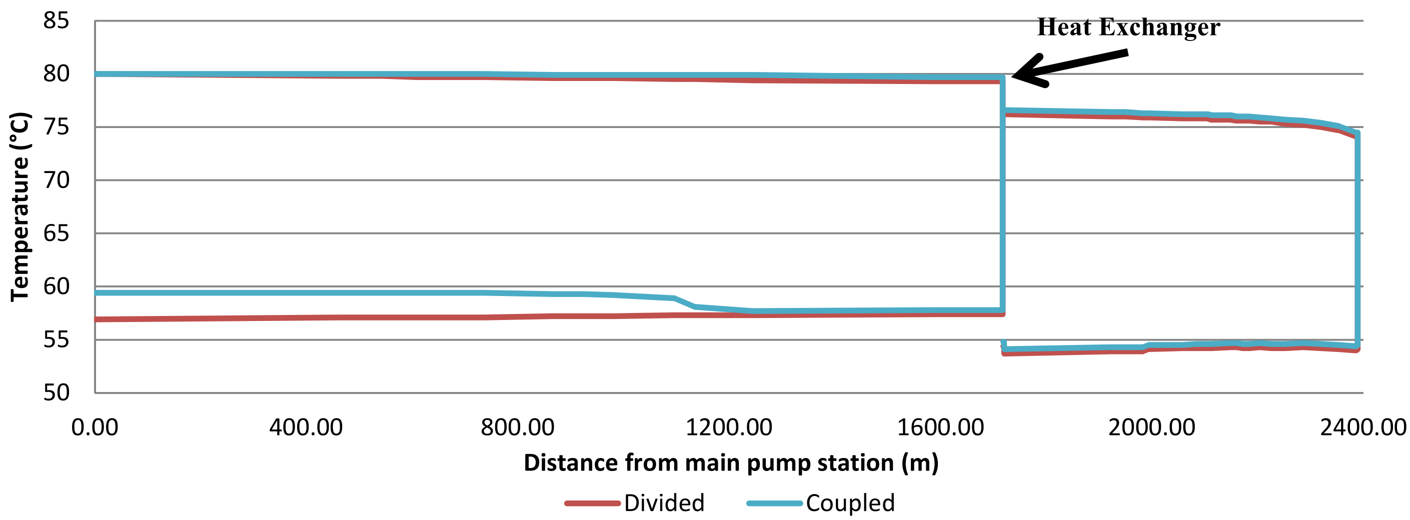

Figure 18 Temperature distribution of dh system at full load - divided and coupled

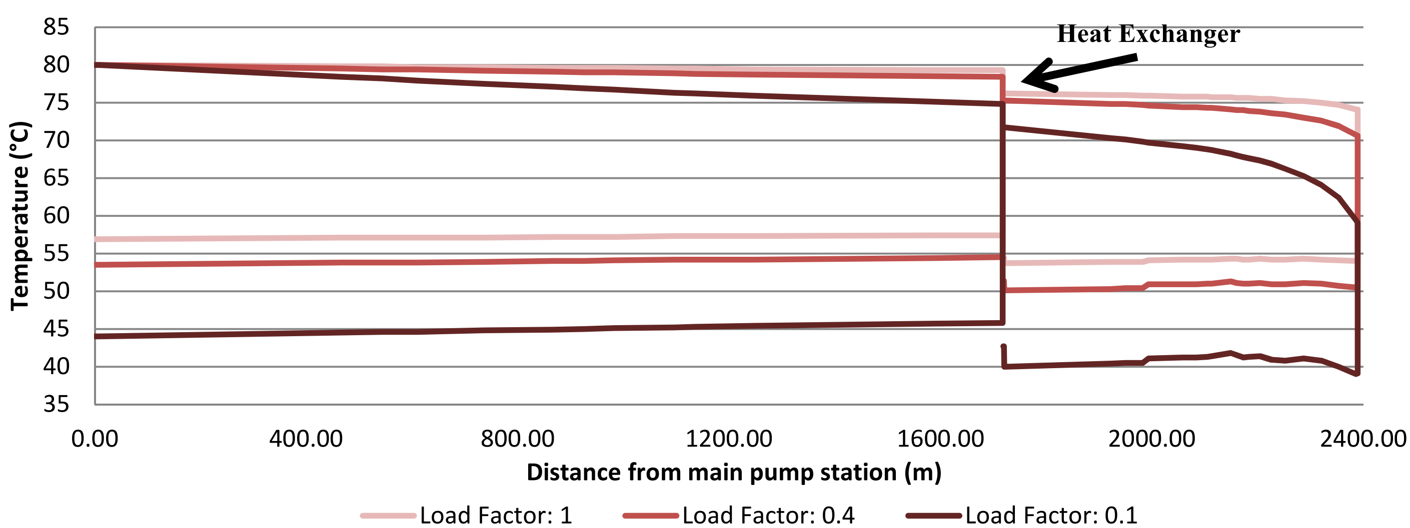

Figure 19 Temperature distribution of dh system with different loading factors - DIVIDED

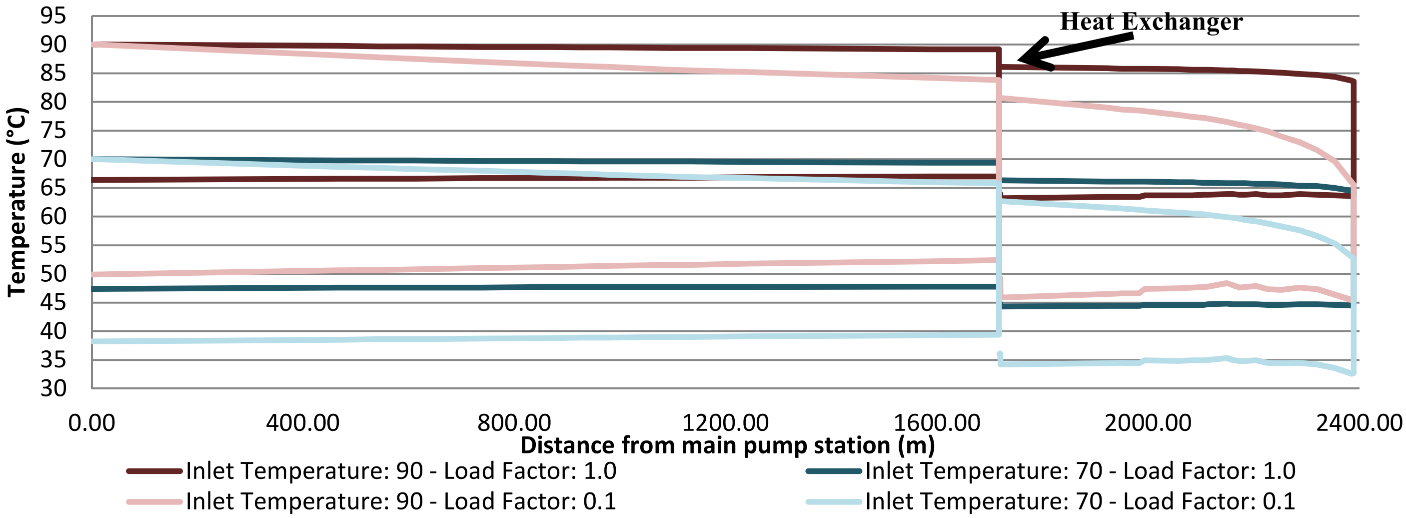

Figure 20 Network response at different operational temperature - divided

CONCLUSION

In this paper, design and simulation of a district heating system were conducted. Basis of the study in 4 steps were heat load determination, thermal & hydraulic design, prediction of annual heat distribution and heat storage tank dimensioning. Performance simulation results were discussed for different cases and aspects based on operational conditions. Summary of the design and performance analysis of the designated district heating system is given below.

- Developed design tool based on assumptions and methodology given in heat load determination is accurate enough and correlates well with a district heating application. It is possible to perform both peak heat load calculation and dynamic simulation for the district heating area. The tool could be used for design and simulation of any heating application as well.
- Assumptions made in the tool give better response to district heating application rather than assumptions of standards given in TS 2164. % 7 of deviation between assumptions of tool and TS 2164 cannot be ignored. This is because of the fact that %7 deviation might occur in substantial increase of investment costs in such big DH systems that have long networks. Therefore, it is important to take into account of all possible factors that influence heat transfer in buildings as done in this study.
- District heating system has a good response to different operating conditions. Possible interferences such as cavitation, pressure loss or heat loss could be simulated and detected in TERMIS software. In addition, at low load factors, end-user temperature could be less than that in full load. Thus, plant supply temperature must be set carefully.
- District heating system could be dynamically monitored and financial analysis & planning on energy consumption could be performed. Dynamic monitoring carried out in this study gives us a chance to modify system heat losses. As an example, if infiltration losses are high, it is a clue to modify doors and windows in dwellings.
- It is possible to take into account of potential zones for further settlements and new district heating sites could be conjugated with current ones with methodology stated in this study. Since thermal performance of DH system is not influenced substantially, hydraulic performance must be carried out carefully. Pressure distribution is easily affected by coupling with new settlement areas. By considering pressure decline, potential zone concept enables us to design sustainable district heating systems.

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NOMENCLATURE

se: steam extraction ratio from cross-over pipe (%)
k_t: thermal conductivity (W/mK)
q_r: solar radiation (W/m^2)
H_u: lower heating value of lignite (kWh/kg)
U: overall heat transfer coefficient (W/mK)
D: overall average heat transfer coefficient (W/mK)
Q: thermal energy (J)
F: solar radiation factor
A: area (m^2)
T: temperature (˚C)
Z: heat loss increase factor (%)
R: thermal property of the room
H: thermal property of the structural element (Wh/m^{3}K)
$\dot{Q}$: heat transfer rate (kW)

$\dot{V}$: volumetric flow rate (m^3/h)
h: convection heat transfer coefficient (W/m^2K)
a:air leakage rate per unit gap of windows. (m^3/mh)
l:leakage gap peripheral length (m)
t: time (s)
m: mass (kg)
Δt: temperature difference
Σ(al):air leakage rate (m^3/h)

Greek Letters

η: efficiency
ε: roughness

Subscripts

DH: district heating
PP: power plant
MPS: main pump station
LPS: local pump station
HS: heat storage
DHW: district hot water
th: thermal
ex: exergetic
int: interior
ext: exterior
in: inlet
out: outlet
nh: non-heated

REFERENCES

[1] Euroheat & Power, www.euroheat.org, Statistics, Statistics overview 2011

[2] H.H. Erdem, B. Sahin, I. Teke, S.H. Sevilgen, A. Dagdas, B. Cetin, A. V. Akkaya, Research and development of methods to benefit from thermal power plant surplus heats and district heating application, Yildiz Technical University, Mechanical Engineering Faculty, (Project No. 105G099). Report No: IP2.2, 2007 (in Turkish)

[3] H. H. Erdem, A. Dagdas, S. H. Sevilgen, B. Cetin, A. V. Akkaya, B. Sahin, I. Teke, C. Gungor, S. Atas, Thermodynamic analysis of an existing coal-fired power plant for district heating/cooling application, Applied Thermal Engineering 30 (2010) 181-187

[4] A.J. Heller, Heat-load modeling for large systems, Applied Energy 72 (2002) 371-387

[5] H. Li, S. Svendsen, Energy and exergy analysis of low temperature district heating network, Energy, 45 (2012) 237-246

[6] T. A. Koiv, A. Mikola, U. Palmiste, The new dimensioning method of the district heating network, Applied Thermal Engineering 71 (2014) 78-82

[7] A. Yan, J. Zhao, Q. An, Y. Zhao, H. Li, Y. J. Huang, Hydraulic performance of a new district heating systems with distributed variable speed pumps, Applied Energy 112 (2013) 876-885

[8] M. A. Ancona, F. Melino, A. Peretto, An optimization procedure for district heating networks, Energy Procedia 61 (2014) 278-281

[9] P. Jie, N. Zhu, D. Li, Operation optimization of existing district heating systems, Applied Thermal Engineering 78 (2015) 278-288

[10] A. C. Gurses, Isıtma ve iklimlendirme (HVAC) sistemlerinde yük hesabi yontemleri, National HVAC&R Congress, 1993, Kli 019 (In Turkish)

[11] O. F. Genceli, I. C. Parmaksizoglu, Kalorifer Tesisati, Mechanical Engineering Chamber Publication MMO/352/7, 2012 (In Turkish)

[12] T. Yilmaz, H. Bulut, Turkiye İcin Yeni Dis Ortam Sicaklik Tasarim Degerleri, The 5th National HVAC&R Congress, 2001, 293-311 (In Turkish)

[13] M. Bilgili, E. Simsek, B. Sahin, Determination of The Soil Temperatures in Aegean Region by Artificial Neural Network Method, Journal of Thermal Science and Technology 30 1 (2010) 121-132

[14] CIBSE guide A and J, GVA/15, 2015, Chartered Institution of Building Services Engineers

[15] S. Darby, R. White, Thermal comfort, Oxford University, Environmental Change Institute, Background document C for the %40 house report, 2005

[16] NAHB Research Center, Domestic hot water system modeling for the design of energy efficient systems, 2002

[17] Water heater sizing guide, PV 592 11 (2011), PVI Industries, LLC

[18] H. Gadd, S. Werner, Daily heat load variations in Swedish district heating systems, Applied Energy, 106 (2013) 47-55

[19] R. Hendron, J. Burch, Development of standardized domestic hot water event schedules for residential buildings, Energy Sustainability Conference, NREL/CP-550-40874, 2007

[20] J. D. Wit, Heat storages for CHP optimization, Danish Gas Technology Center, PowerGen Europe 1-17 (2007)

[21] K. Mogens, A. Jorgen, Heat accumulators, Hot|Cool 1-4 (2004), ISSN 0904 9684