

Advanced Control of a District Heating System with High Residential Domestic Hot Water Demand

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Abstract. Proper adjustment of domestic hot water (DHW) load structure can balance energy demand with the supply. Inefficiency in primary energy use prompted Omsk DH company to be a strong proponent of a flow controller at each substation. Here the return temperature is fixed to the lowest possible value and the supply temperature is solved. Thirty-five design scenarios are defined for each load deviation index with equally distributed outdoor temperature ranging from +8 for the start of a heating season towards extreme load at temperature of -26°C. All the calculation results are listed. If a flow controller is installed, the customers might find it suitable to switch to this type of DHW supply. Considering an option with direct hot water extraction as usual and a flow controller installed, the result indicates that the annual heat consumption will be lower once network temperatures during the fall or spring months are higher. The heat load profiles obtained here may be used as input for a simulation of a DH substation, including a heat pump and a tank for thermal energy storage. This design approach offers a quantitative way of sizing temperature levels in each DH system according to the listed methodology and the designer's preference.

1 Introduction

District heating (DH) systems have historically consisted of large-scale conventional production units owned by utilities. Thermal energy produced at a DH plant is transported via a branched network and is finally transferred to the consumer. This connection is commonly called a substation or an energy transfer station. However, as the knowledge and awareness of environmental problems (e.g. greenhouse gas (GHG) emission) grows, there has been a change in the approach. For instance, Malmö, Sweden is pioneering building-level facilities, creating the concept of prosumers [1] – consumers of heat that can also provide heat into the system. This has driven an energy company (1) to modernize equipment at a demand side and (2) to lower network operating temperatures, thus leading to the so called fourth generation district heating (4GDH).

On the first subject, demand side measures are measures to manipulate the load curve in a certain way through either decreasing total demand or shaping its profile in order to achieve a more suitable profile for heat supply. An action is undertaken in any part of a building HVAC system including a hydraulic or an all-air installation as well as in domestic hot water (DHW) units. A successful modification may show a specific impact onto the load curve particularly peak-load shifting [2]. In turn, its benefits are cutting down installed capacity, increasing utilization of energy supply and distribution system and so improving the operational efficiency. Besides the temporal distribution, DHW

structure is also a property of total load [3]. DHW structure refers to the load deviation index. The supply capacities of different types of energy may be fixed. For instance, in a network optimization nominal capacities are used [4,5].

Secondly, 4GDH brings an idea of distributing heat at temperature below 45°C and using a heat pump at a consumer substation to provide the appropriate temperature required for space heating (SH) and DHW production [6]. If multiple heat pumps are installed, the seasonal coefficient of performance (SCOP) of the entire system may be calculated as a weighted average of the SCOPs of the reference buildings, using the energy needs as weights [7]. It has been estimated that widespread use of a heat pump at an energy transfer station could reduce GHG by 1.25 billion tonnes over next 30 years [8].

For each desired combination of such stations in a given city, Zarin Pass et al. [9] calculate the combined hourly heating, cooling, and DHW load profiles. In Ref. [10] DHW consumption profiles were assigned based on the occupancy schedule.

Im et al. [11] present temperature profiles of a DH system in winter and summer. Due to heat losses in winter season, significant temperature drop of supply water occurs. In Ref. [12], authors developed an advanced thermal model for the temperature distribution along a network. As it can be seen in Ref. [13], the heat losses by assuming standard pipe parameters are higher (96.8% more) than the one found by assuming a constant heat transfer coefficient. The DHW is the key

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component suffering from heat losses: the heat supplied can go to a heat exchanger or directly to a building extracted from supply/return pipe as more common in Russia [14]. Every heat exchanger needs a specified temperature range and thermal capacity. Once a specified temperature range is not met, direct connection cannot operate.

In comparison to previous works analyzing energy distribution, in present paper efficiency improves with increasing share of DHW supply. The aim here is to research an opportunity of an advanced control of a DH system with high residential DHW demand, e. g. with average DHW–SH heating ratio $\frac{Q_{DHW}^{av}}{Q_{SH}} = 0.3$.

2 Materials & Methods

District heating (DH) systems have historically consisted of large-scale conventional production units owned by utilities. Thermal energy produced at a DH plant is transported via a branched network and is finally transferred to the consumer. This connection is commonly called a substation or an energy transfer station. However, as the knowledge and awareness of environmental problems (e.g. greenhouse gas (GHG) emission) grows, there has been a change in the approach. For instance, Malmö, Sweden is pioneering building-level facilities, creating the concept of prosumers [1] – consumers of heat that can also provide heat into the system. This has driven an energy company (1) to modernize equipment at a demand side and (2) to lower network operating temperatures, thus leading to the so called fourth generation district heating (4GDH).

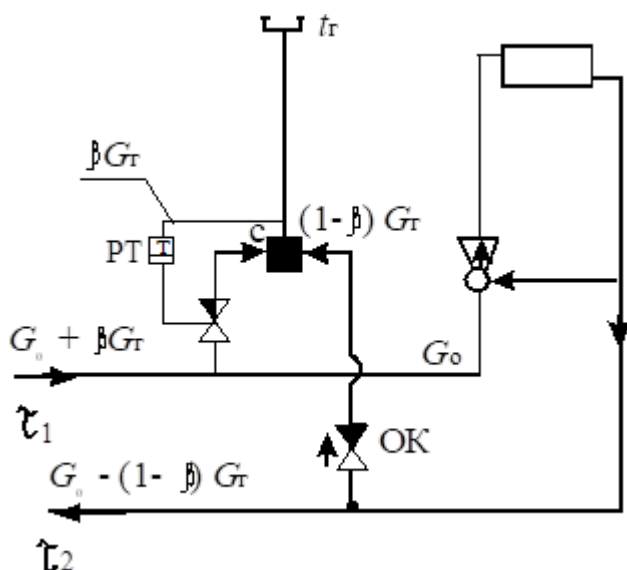


Fig. 1. Substation layout: PT temperature control valve, C mixing box, OK check valve.

Proper adjustment of DHW load structure can balance energy demand with the supply. Especially when DH or combined heat-and-power (CHP) plants are

adopted, an appropriate average DHW–SH heating ratio ($\frac{Q_{DHW}^{av}}{Q_{SH}}$) at a demand side can maximise the operational efficiency since this ratio determines the waste heat – heat storage capacity of return water – utilization. When $\frac{Q_{DHW}^{av}}{Q_{SH}}$ (average DHW demand to design SH demand ratio) < 0.15, the mass flows in the SH pipes are almost the same as those mass flows in the corresponding DH network pipes implying an appropriate pressure drop. This creates thermal peaks, which may lead to sub-optimal dispatch of CHP and heat-only boiler plants, and therefore increase fuel consumption. When a DHW–SH ratio is treated, different approaches are possible using e.g. the design value of one certain objective or a specific weighting based on an entire control strategy. In this work, as well as in Ref. [15] the way of choosing minimal outdoor temperature is used because in this case the effect of curve manipulation is better visible. The temperature profiles of the heating network, as it can be seen from Fig. 2, shows that all the return temperatures are more than or equal to the minimal value specified at DHW taps (i.e. 50 °C).

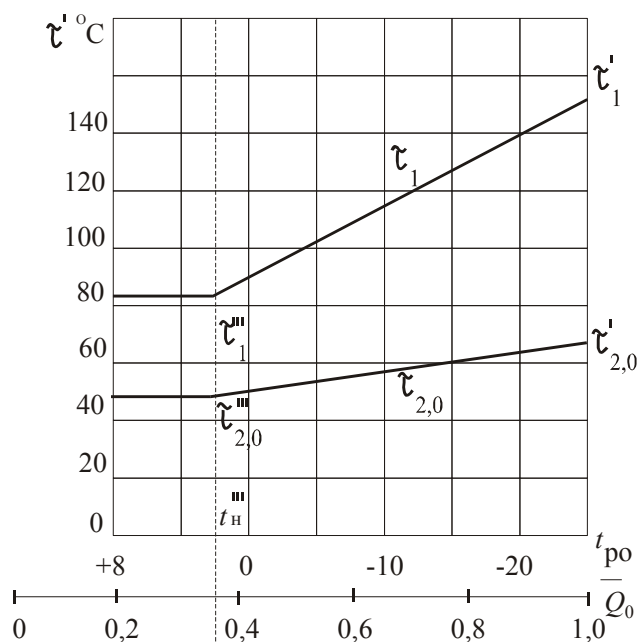


Fig. 2. Network temperatures as a function of outdoor temperature.

The supply temperature reaches its lowest value of 82°C when outdoor temperature is 2°C or above. Design flow rate for DHW need is as follows

$$G_{DHW} = 3600 \frac{Q_{DHW}}{c(t_{DHW} - t_t)} \quad (1)$$

where Q_{DHW} is DHW heat demand [MW], c is specific capacity of water [kJ/kgK], t_{DHW} is DHW water temperature, and t_t is tap water temperature.

DHW extraction from supply line G_{DHW}^s and return one G_{DHW}^r can be evaluated

$$G_{DHW}^s = \beta G_{DHW} \quad (2)$$

$$G_{DHW}^r = (1 - \beta)G_{DHW} \quad (3)$$

where β is a share of DHW extraction from supply line.

Without considering flow loss in a mixing box, the sum of all energy flowing in has to be the same as the sum of energy flowing out [16]

$$G_{DHW} t_{DHW} = G_{DHW}^s T_1 + G_{DHW}^r T_{2,0} \quad (4)$$

where τ_1 is network supply temperature, and $\tau_{2,0}$ is network return temperature.

The share of DHW extraction from a supply line can also be acquired by Eqs. (2) and (3)

$$\beta = \frac{t_{DHW} - T_{2,0}}{T_1 - T_{2,0}} \quad (5)$$

In all the cases, there is a direct correlation between DHW flow rate and ratio $(t_{DHW} - t_i)/(\tau_{2,0} - t_i)$, indicating that DH network return temperature does have significance for system performance. The higher the ratio applied, the better performance can be achieved. Comparing results between $\beta = 0$ and $\beta = 1$ simulations, one can see improved hydraulic operation whereas the temperature of return water also decreases [17].

DH network flow rate (to cover DHW need only) can be obtained as follow

$$G_{DHW} = 3600 \frac{Q_{DHW}}{c(\tau_{2,0} - t_i)} \quad (6)$$

3 Results & Discussion

DH network flow rate (to cover DHW need only) when $\tau_{2,0} \leq 60^\circ\text{C}$

$$G_{DHW} = \frac{1.1 \cdot 55.5 \cdot 3600}{4.19(60 - 5)} = 0.950$$

[t/h], and

when $t_{out} = -26^\circ\text{C}$ and $\tau_{2,0} = 70^\circ\text{C}$

$$G_{DHW} = \frac{1.1 \cdot 55.5 \cdot 3600}{4.19(70 - 5)} = 0.810$$

[t/h].

For evaluation of the technological performance of resource consumption, share of DHW extraction from supply line at an ambient temperature of $+8^\circ\text{C}$ is determined through (5)

$$\beta = \frac{60 - 32.9}{63.8 - 32.9} = 0.875$$

Thirty-five design scenarios are defined for each load deviation index with equally distributed outdoor temperature ranging from $+8^\circ\text{C}$ for the start of a heating season towards extreme load at temperature of -26°C . All the calculation results are listed in Table 1.

In EU DH systems run with supply line water temperatures between $50\text{--}55^\circ\text{C}$ or $60\text{--}70^\circ\text{C}$ with return line water temperatures of 25°C to 40°C and still meet heating requirements for SH and DHW in residential or commercial buildings [8]. Im & Liu [11] indicate that such difference between return and supply temperatures does not succeed in reaching the design temperature of SH or operating temperature of auxiliary equipment, and more heat is required from a CHP plant. Moreover, these temperature levels are not acceptable when a heat distribution network operates in Russia within the context of outdoor temperatures of -30°C and below [18]. The heat load profiles obtained here may be used as input for a simulation of a DH substation, including a heat pump [19] and a tank for thermal energy storage [6]. It should also be mentioned that a DH operator may also vary this temperature on an annual level [20], but it is expected to be close to the suggested value [21]. The different deviation values may be accomplished by changing the ratio of loads between only-heated and DHW-supplied buildings [22].

4 Conclusions

Due to inefficiency, heat production price may increase over few years. One of the main reasons a DH system is appreciated by the consumers is the relatively stable SH and DHW prices they offer. Consequently, the increase in heat prices could lead to dissatisfaction and potential disconnections from a distribution system, further negotiating its feasibility. This design approach therefore offers a quantitative way of sizing temperature levels in each DH system according to the listed methodology and the designer's preference. It overcomes the non-optimum design when using SH values for base load design, since the proper adjustment of DHW load structure is kept.

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Table 1. Results of the temperature and flow analysis

| t_{out} [°C] | Q_o | G_o | $\tau_{1,o}$ [°C] | $\tau_{2,o}$ [°C] | τ_1 [°C] | τ_2 [°C] | β | G_{SH} [t/h] | G_{DHW} [t/h] | G_{DHW}^s [t/h] | G_{DHW}^r [t/h] | G_1 [t/h] | G_2 [t/h] |
|-------------------|-------|-------|----------------------|----------------------|------------------|------------------|---------|-------------------|--------------------|----------------------|----------------------|----------------|----------------|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| 8 | 0.227 | 0.582 | 53.1 | 34.9 | 64.1 | 32.8 | 0.87 | 1.157 | 0.954 | 0.830 | 0.124 | 1.987 | 1.033 |
| 7 | 0.250 | 0.618 | 56.2 | 36.2 | 66.6 | 34.2 | 0.80 | 1.227 | 0.954 | 0.759 | 0.194 | 1.987 | 1.033 |
| 6 | 0.273 | 0.650 | 59.2 | 37.4 | 69.1 | 35.6 | 0.73 | 1.292 | 0.954 | 0.695 | 0.259 | 1.987 | 1.033 |
| 5 | 0.295 | 0.681 | 62.3 | 38.6 | 71.6 | 36.9 | 0.67 | 1.352 | 0.954 | 0.635 | 0.319 | 1.987 | 1.033 |
| 4 | 0.318 | 0.709 | 65.3 | 39.8 | 74.1 | 38.2 | 0.61 | 1.408 | 0.954 | 0.579 | 0.375 | 1.987 | 1.033 |
| 3 | 0.341 | 0.735 | 68.3 | 41.0 | 76.6 | 39.5 | 0.55 | 1.459 | 0.954 | 0.527 | 0.426 | 1.987 | 1.033 |
| 2 | 0.364 | 0.759 | 71.3 | 42.2 | 79.1 | 40.7 | 0.50 | 1.507 | 0.954 | 0.479 | 0.474 | 1.987 | 1.033 |
| 1 | 0.386 | 0.781 | 74.2 | 43.3 | 81.5 | 42.0 | 0.46 | 1.552 | 0.954 | 0.435 | 0.519 | 1.987 | 1.033 |
| 0 | 0.409 | 0.802 | 77.2 | 44.4 | 84.0 | 43.2 | 0.41 | 1.594 | 0.954 | 0.393 | 0.560 | 1.987 | 1.033 |
| -1 | 0.432 | 0.822 | 80.1 | 45.5 | 86.4 | 44.4 | 0.37 | 1.632 | 0.954 | 0.354 | 0.599 | 1.987 | 1.033 |
| -2 | 0.455 | 0.840 | 83.0 | 46.6 | 88.9 | 45.6 | 0.33 | 1.669 | 0.954 | 0.318 | 0.636 | 1.987 | 1.033 |
| -3 | 0.477 | 0.857 | 85.9 | 47.7 | 91.3 | 46.7 | 0.30 | 1.703 | 0.954 | 0.284 | 0.670 | 1.987 | 1.033 |
| -4 | 0.500 | 0.873 | 88.8 | 48.8 | 93.7 | 47.9 | 0.26 | 1.735 | 0.954 | 0.252 | 0.702 | 1.987 | 1.033 |
| -5 | 0.523 | 0.888 | 91.7 | 49.9 | 96.1 | 49.0 | 0.23 | 1.765 | 0.954 | 0.222 | 0.731 | 1.987 | 1.033 |
| -6 | 0.545 | 0.902 | 94.5 | 50.9 | 98.5 | 50.2 | 0.20 | 1.793 | 0.954 | 0.194 | 0.760 | 1.987 | 1.033 |
| -7 | 0.568 | 0.916 | 97.4 | 51.9 | 100.9 | 51.3 | 0.18 | 1.819 | 0.954 | 0.168 | 0.786 | 1.987 | 1.033 |
| -8 | 0.591 | 0.928 | 100.2 | 53.0 | 103.3 | 52.4 | 0.15 | 1.844 | 0.954 | 0.143 | 0.811 | 1.987 | 1.033 |
| -9 | 0.614 | 0.940 | 103.1 | 54.0 | 105.7 | 53.5 | 0.12 | 1.868 | 0.954 | 0.119 | 0.835 | 1.987 | 1.033 |
| -10 | 0.636 | 0.951 | 105.9 | 55.0 | 108.1 | 54.6 | 0.10 | 1.890 | 0.954 | 0.097 | 0.857 | 1.987 | 1.033 |
| -11 | 0.659 | 0.962 | 108.7 | 56.0 | 110.5 | 55.6 | 0.08 | 1.911 | 0.954 | 0.076 | 0.878 | 1.987 | 1.033 |
| -12 | 0.682 | 0.972 | 111.5 | 57.0 | 112.8 | 56.7 | 0.06 | 1.931 | 0.954 | 0.056 | 0.898 | 1.987 | 1.033 |
| -13 | 0.705 | 0.981 | 114.3 | 57.9 | 115.2 | 57.8 | 0.04 | 1.950 | 0.954 | 0.037 | 0.917 | 1.987 | 1.033 |
| -14 | 0.727 | 0.990 | 117.1 | 58.9 | 117.6 | 58.8 | 0.02 | 1.968 | 0.954 | 0.019 | 0.934 | 1.987 | 1.033 |
| -15 | 0.750 | 0.999 | 119.9 | 59.9 | 119.9 | 59.9 | 0.00 | 1.985 | 0.954 | 0.002 | 0.951 | 1.987 | 1.033 |
| -16 | 0.773 | 1.000 | 122.6 | 60.8 | 122.6 | 60.8 | 0.00 | 1.987 | 0.940 | 0.000 | 0.940 | 1.987 | 1.047 |
| -17 | 0.795 | 1.000 | 125.4 | 61.8 | 125.4 | 61.8 | 0.00 | 1.987 | 0.924 | 0.000 | 0.924 | 1.987 | 1.063 |
| -18 | 0.818 | 1.000 | 128.2 | 62.7 | 128.2 | 62.7 | 0.00 | 1.987 | 0.909 | 0.000 | 0.909 | 1.987 | 1.078 |
| -19 | 0.841 | 1.000 | 130.9 | 63.6 | 130.9 | 63.6 | 0.00 | 1.987 | 0.895 | 0.000 | 0.895 | 1.987 | 1.092 |
| -20 | 0.864 | 1.000 | 133.7 | 64.6 | 133.7 | 64.6 | 0.00 | 1.987 | 0.881 | 0.000 | 0.881 | 1.987 | 1.106 |
| -21 | 0.886 | 1.000 | 136.4 | 65.5 | 136.4 | 65.5 | 0.00 | 1.987 | 0.867 | 0.000 | 0.867 | 1.987 | 1.120 |
| -22 | 0.909 | 1.000 | 139.1 | 66.4 | 139.1 | 66.4 | 0.00 | 1.987 | 0.854 | 0.000 | 0.854 | 1.987 | 1.133 |
| -23 | 0.932 | 1.000 | 141.9 | 67.3 | 141.9 | 67.3 | 0.00 | 1.987 | 0.842 | 0.000 | 0.842 | 1.987 | 1.145 |
| -24 | 0.955 | 1.000 | 144.6 | 68.2 | 144.6 | 68.2 | 0.00 | 1.987 | 0.830 | 0.000 | 0.830 | 1.987 | 1.157 |
| -25 | 0.977 | 1.000 | 147.3 | 69.1 | 147.3 | 69.1 | 0.00 | 1.987 | 0.818 | 0.000 | 0.818 | 1.987 | 1.169 |
| -26 | 1.000 | 1.000 | 150.0 | 70.0 | 150.0 | 70.0 | 0.00 | 1.987 | 0.807 | 0.000 | 0.807 | 1.987 | 1.180 |

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