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Achieving low return temperature for domestic hot water preparation by ultra-low-temperature district heating

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Abstract

District heating (DH) is a cost-effective method of heat supply, especially to area with high heat density. Ultra-low-temperature district heating (ULTDH) is defined with supply temperature at 35-45 °C. It aims at making utmost use of the available low-temperature energy sources. In order to achieve high efficiency of the ULTDH system, the return temperature should be as low as possible. For the energy-efficient buildings in the future, it is feasible to use ULTDH to cover the space heating demand. However, considering the comfort and hygiene requirements of domestic hot water (DHW) preparation, supplementary heating devices should be combined, which can affect the return temperature in different extents. This study analysed the return temperatures of different types of substations for DHW preparation with ULTDH, and developed improvements in the substation for better energy efficiency. Both the instantaneous and storage-type electric heating methods were Long-term measured as supplementary heating for ULTDH in the case substations in Denmark. We analysed the seasonal impacts of the return temperature from the DHW loop on the overall return temperature of district heating. To achieve lower return temperature and higher efficiency for DHW supply, an innovative substation was devised, which replaced the bypass with an instantaneous heat exchanger and a micro electric storage tank. The energy performance of the proposed substation and the resulting benefits for the DH system by the lower return temperature were investigated

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1. Introduction

District heating is a cost-effective way of utilizing renewable and recycle energy as heating sources for covering the heat demand of the high-heat-density areas. The temperature levels of district heating systems is of great importance for better efficiency. Low supply temperature can increase the efficiency of recovering heat from industrial excess heat and geothermal heat, and can also improve the coefficient of performance (COP) of a heat pump for heat production [1]. Low return temperature can improve the efficiency of flue gas condensation in the heat plant. In addition, the distribution heat loss will be reduced if the distribution heat loss is lowered. Therefore, to implement low-temperature district heating (LTDH) plays an important role in improve the whole district heating system.

However, the comfort and hygiene requirements for heat supply should be taken into account when reducing the DH supply/return temperatures. In Nordic countries, such as Denmark and Sweden, DH supply covers both the space heating (SH) demand and domestic hot water (DHW) demand. For space heating, a comfort room temperature (20-22 °C) can be reached with a supply temperature at 40 °C if efficient heating equipment and operation methods are applied [2]. Regarding to DHW supply, the DHW should be able to be produced at 60 °C and circulated at 50 °C to avoid Legionella [3], and the water temperature at the faucet is required to reach 45 °C for the comfort reasons [4].

This study is based on an ultra-low-temperature district heating project in Denmark, where the heat demand of the test houses are covered by a DH system with supply temperature at 46 °C most of the year. To guarantee comfort and hygiene heat supply for DHW, different types of supplementary heating devices were installed in the house substations. However, the return temperatures of the DHW circuits are various according to the different substation layouts. This study investigated the return temperatures and energy performances resulted by different substations. In addition, a new DHW preparation method with ULTDH was devised, which aims at improving the overall system efficiency and reducing the return temperature to DH.

Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

2. Background of the ULTDH case study

The case project is located in Denmark. The heat source is the industrial excess heat from a local pump factory. A heat pump is used to recover the waste heat and deliver the heat to the heat consumers at 46 °C most of the year. The supply temperature is able to be increased to compensate the extreme cold climate during the winter

2.1. Comparison of return temperatures from different DHW configurations

The DHW preparation configurations play an important role in the average return temperature of the DHW circuits to DH. Two single-family houses in the area were selected for the analyses of this study. Both of the houses have the in-house substation. House #1 uses a storage tank for DHW preparation, while house #2 uses an instantaneous heat exchanger (IHEX) and a direct electric heater. House #1 and house #2 were built in similar time, and both of the houses have two occupants.

The schematics of the substations of the two case houses are shown as the following:

In house #1, a 160L storage tank with 3 kW immersion heater is installed. The domestic cold water (DCW) is preheated by the district heating, and is further heated by the immersion heater in the tank to the set-point temperature (50 °C). Since DHW is stored in the tank, the tank should have sufficient capacity to heat the water to 60 °C.
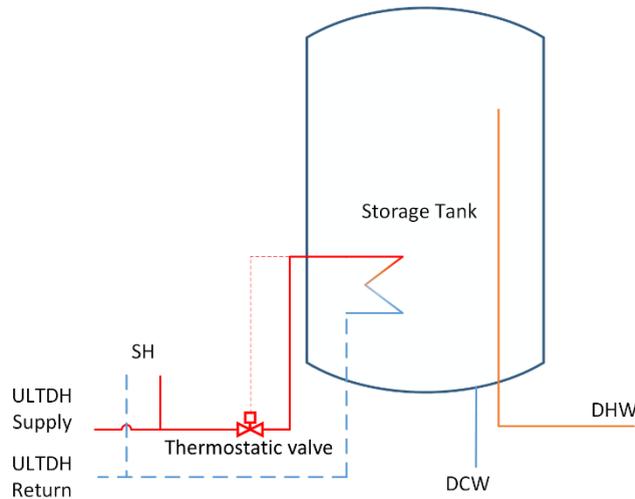
Fig. 1 Schematic of the DHW configuration in house #1 with storage tank
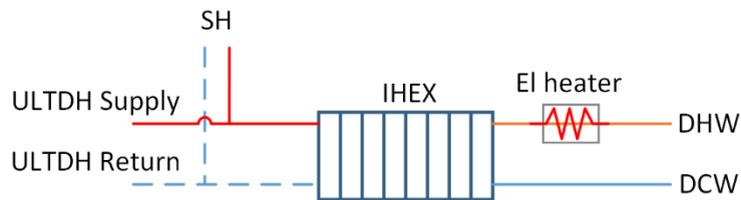
Fig. 2 Schematic of the DHW configuration in house #2 with IHEX and electric heater

In house #2, an instantaneous heat exchanger with bypass function is installed. The DCW is preheated by the ULTDH through the heat exchanger, and is further heated by the direct electric heater after then heat exchanger. Since the total volume of the DHW in the distribution pipes inside the house is very small, the risk of Legionella is eliminated. The set point temperature of the electric heater was made at 45 °C to meet the comfort requirement. In Denmark, the waiting time for DHW at comfort temperature should be no longer than 10s [4]. Considering the transmission time in the pipes, normally bypass is operated for the IHEX. The bypass set-point temperature in the case house was made to 40 °C.

Long-term measurements were performed for the test houses. energy meters were located on both the DH main pipe (including both SH and DHW) and the DHW preparation circuit. The meters can measure the overall supply and return temperatures, flowrates and supply heat of ULTDH, as well as the values of the DHW preparation loop. The measurements of August 2015 and January 2016 were selected to represent for the summer season and winter season. The impact of the return temperature from the DHW circuit on the overall return temperature to DH was also investigated.

2.2. Results of the return temperatures from different DHW configurations

The results of the temperature measurements in the summer season and winter season in the two houses are shown in the following diagrams:
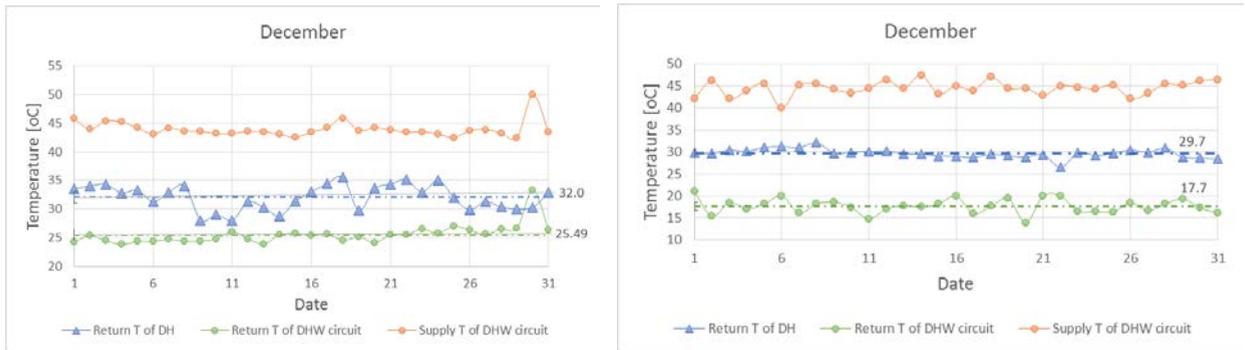

Fig. 3 (a) House #1; (b) House #2 Temperature measurements of return temperature in December

The blue curves represent the overall return temperature of district heating, which integrates the return temperatures of both the space heating circuit and domestic hot water circuit. From the diagrams, the supply temperatures of the ULTDH system were both around 45 °C when they reach the substations in house #1 and house #2. However, house #2 with IHEX and electric heater had much lower return temperature for DHW preparation compared with house #1 with a storage tank.

The average return temperature to DH and the return temperature of the DHW circuit on monthly basis as well as the temperature difference are shown in the following table:

Table 1. Average return temperature of the DHW circuit , average return temperature of DH and the temperature difference with standard variation of December

	House #1		House #2	
	Average	Standard variation	Average	Standard variation
Return T of DH [°C]	32.0	2.2	29.7	1
Return T of DHW circuit	25.5	1.7	17.7	1.7
Supply T of DHW circuit	44	1.4	44.5	1.6
Δ T	18.5	1.6	26.8	2.7

From **Error! Reference source not found.**, the average return temperature of house #2 with IHEX and electric heater is 7.8 °C lower than house #1 with a storage tank. With similar supply temperature, the temperature difference for DHW preparation with IHEX and electric heater is 8.3 °C larger compared with the substation with storage tank. That indicates that the instantaneous preparation of DHW with IHEX and electric heater has better energy and exergy efficiency than the storage type. The difference of the overall return temperature to DH is insignificant between house #1 and house #2. The overall return temperature of house #2 is only 2.3 °C lower than that of house #1. However, the overall return temperature of DH also includes the space heating flow. During the winter time, the space heating flow dominates the overall DH flow, which can have a more significant impact on the overall return temperature. The higher overall return temperature also indicated that the return temperature of the space heating circuit is higher.
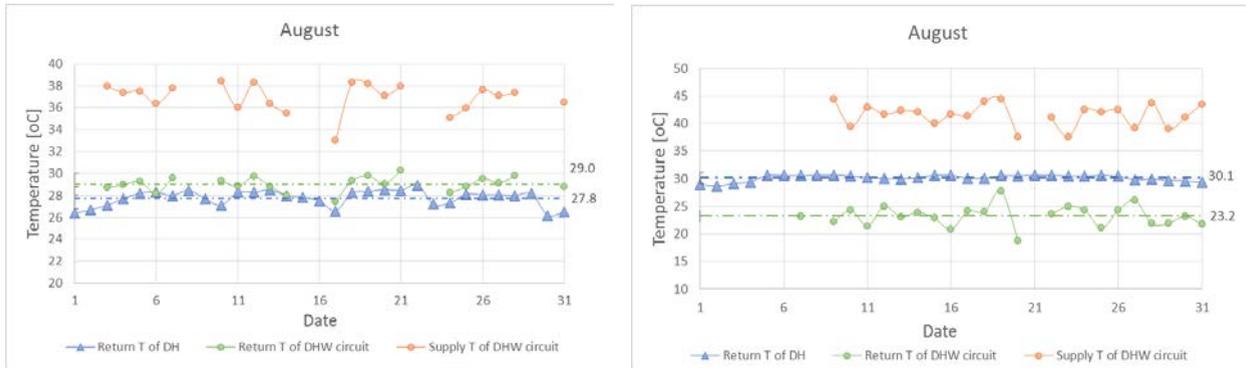
Fig. 4 Temperature measurements of return temperature in August in house #1 and #2

Error! Reference source not found. shows the temperature measurements during the summer period. The periods without any data points means the occupants were leaving for a vacation.

The DH supply temperature was lowered during the summer time. The results in house #1 shows different trend compared with the winter time. As shown in **Error! Reference source not found.** (a), the return temperature of DHW circuit in house #1 is slightly higher than the overall DH return temperature.

In terms of house #2, the average return temperature of the DHW circuit is higher in summer, but still lower than the overall return temperature of DH, which indicates the space heating loads in the house during the summer.

The average temperatures of August with standard variation and the actual temperature difference for DHW production are calculated, the results are shown in the following table:

Table 2 Average return temperature of the DHW circuit , average return temperature of DH and the temperature difference with standard variation of August

	House #1		House #2	
	Average	Standard variation	Average	Standard variation
Return T of DH [°C]	27.8	0.7	30.1	0.6
Return T of DHW circuit	29.0	0.7	23.2	2.0
Supply T of DHW circuit	36.9	1.3	41.5	2.0
Δ T	7.9	0.8	18.3	2.7

In August, the return temperature from instantaneous DHW production is 5.8 °C lower compared with the storage type. However, compared to the winter period, the return temperature of the DHW circuit in both houses increased. This might be caused by the lower efficiency of the heat exchanging process due to the lower DH supply temperature. As a result, the actual temperature difference for DHW production in summer season reduced by 10.6 °C for house #1 and 8.5 °C for house #2. According to the temperature difference for DHW production, the instantaneous DHW production still performed better than the storage type.

Comparing the return temperatures of DHW circuit in winter and summer, house #2 has more significant temperature increase in the summer period. One reason can be the operation of bypass, which is used to keep the service pipe warm between the DHW draw offs, so that the consumers can get DHW at comfort temperature within acceptable waiting time. However, since the bypass flow has to be operated at high temperature and does not exchange heat with DHW, the operation of bypass will result in extra heat losses and higher return temperature due to direct mixing into the return flow. Therefore, improvements of the DHW configurations are expected by avoiding the bypass.

3. New DHW configuration to achieve lower return temperature

According to the Danish standard, the peak load of DHW is 32.3 kW. If no bypass is operated, the power of the electric heater should be as large as 32.3 kW during the beginning of the tapping, so that DHW can be heated to comfort temperature immediately. However, the capacity of the power supply then has to be increased substantially compared to the normal supply. Therefore, an electric heater with small storage volume is devised to replace the bypass function and to avoid the too large starting power for DHW production.

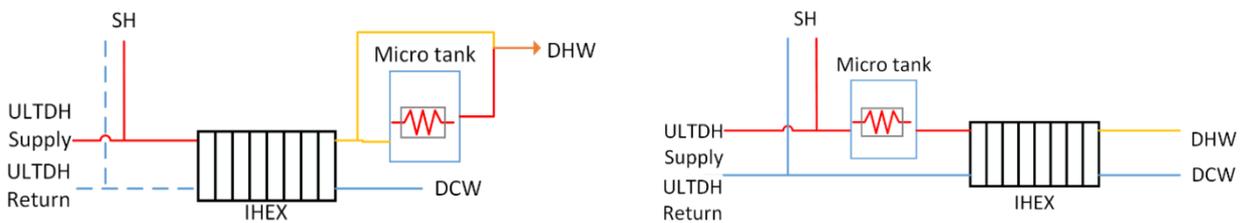The schematics of the new DHW configurations are shown in the following diagrams:

Fig. 5 (**a**) Micro tank installed on the consumer side; (b) micro tank installed on the primary side

As shown in the diagrams, the micro tank with small storage volume of hot water is used to buffer the peak load of the starting power. As a result, an normal electrical heater can be used without enlarging the capacity of the power transmission.

The system configuration and the dimension of the micro tank can vary according to the supply temperature of LTDH as well as the location of the micro tank. The operation of the micro tank is also different consequently.

As shown in Figure 5 (a), DCW is preheated by DH through the heat exchanger. Afterward, the preheated water is further heated by the micro tank and is stored in it. To avoid Legionella, the water in the tank is heated to 60 °C [3]. When DHW draw off occurs, the hot water from the tank will mix with the hot water preheated from DH to achieve the comfort temperature (45 °C for kitchen use and 40 °C for other uses).

The other type of the configuration is to install the micro tank on the primary side, as Figure 5 (b) shows. The micro tank is used to heat and store the DH water. Therefore, the DHW circuit has no storage or circulation, which allows the set-point temperature of the micro tank to be lower than 60 °C.

3.1. Micro tank systems with different ULTDH supply temperature levels

The supply temperature of ULTDH were assumed to 30 °C, 40 °C, and 45 °C as three scenarios for comparison. The electric heater in the tank was assumed to be a normal product with the power of 2 kW for all scenarios. In accordance with the Danish standard [4], the peak load of the DHW supply is 32.3 kW, which assumes one shower and one kitchen tapping occur simultaneously. The shortest interval between two tappings of the same

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type is 20 minutes. Therefore, the volume of the micro tank can be decided. The parameters for dimension the micro tank are shown in the following table:

Table 3 Parameters for micro tank dimension

	Micro tank on consumer side	Micro tank on primary side
Demand for kitchen use	45 °C with 15 L water consumption	
Demand for shower	40 °C with 42 L water consumption	
Interval time between tappings	20 min	
Electric heater power	2 kW	
DCW temperature	10 °C	
Set point temperature of then tank	60 °C	60 °C

The IHEX are assumed to be the same one used in the case study, which is specialized for LTDH substations and can reach the return temperature of 18.8 °C with effective cooling [5]. The temperature difference of the heat exchanging process through the heat exchanger was assumed to 5 °C. It was assumed that the micro tank should contain enough hot water to cover one peak load of DHW at least. The electric heater is switched on as soon as the draw off finished, and should be able to prepare sufficient hot water for the next draw off with peak load.

For the micro tank installed on the consumer side, to cover one peak DHW load, the required water flow at 60 °C can be calculated as:

$$V_a = (t_k - t_{pre})/(t_{tank} - t_{pre}) * V_k + (t_{sh} - t_{pre})/(t_{tank} - t_{pre}) * V_{sh} \tag{1}$$

where

t_k, t_{sh} are the DHW temperature for kitchen use and shower [°C],

t_{pre} is the temperature of DHW preheated by ULTDH [°C],

t_{tank} is the set-point temperature of micro tank, here is 60 [°C],

V_k, V_{sh} are the flow for one kitchen tapping and one shower according to the standard [L].

If the assumed 2 kW electric heater is insufficient for preparing DHW at peak load within 20 min interval, extra volume should be added to V_a for the tank dimension. Otherwise, the micro tank was dimensioned as V_a. The peak load of the electricity can be calculated as:

$$P_{max}^a = \left(c \cdot m_k \cdot (t_k - t_{pre}) + c \cdot m_{sh} \cdot (t_{sh} - t_{pre}) \right)/\tau_{inter} \tag{2}$$

where

c is the specific heat of water [kJ/kg·°C],

m_k, m_sh are the mass flow of kitchen tapping and shower [kg],

τ_inter is the interval time [s].

For the micro tank on the primary side, the DH water flowing out of the tank is 50 °C for all three scenarios with different ULTDH supply temperature. The required water flow was calculated as:

$$V_b = \left((t_k - t_{dcw}) * V_k + (t_{sh} - t_{dcw}) * V_{sh} \right) / (t_{tank} - t_{dhr}) \tag{3}$$

where

t_{dcw} is the temperature of DCW [°C],

t_{dhr} is the return temperature from the heat exchanger [°C].

For the micro tank on the primary side, the peak load of the electric heater was calculated differently compared to the tank on the consumer side, since the water from the tank is unnecessary to mix with other flows but to heat the DCW directly.

$$P_{max}^b = \left(c \cdot m_k \cdot (t_k - t_{dcw}) + c \cdot m_{sh} \cdot (t_{sh} - t_{dcw})\right) \cdot (t_{tank} - t_{dhs})/(t_{tank} - t_{dhr})/\tau_{inter} \qquad (4)$$

where

t_{dhs} is the supply temperature of ULTDH [°C].

3.2. Comparison with direct electric heater with bypass function

Comparisons were made between the storage type electric heater system and direct electric heater system with bypass function. All the systems were assumed to supply the equivalent DHW demand, which is 250 L/ m2 annually. The service pipe was assumed to have the length of 6m with heat loss coefficient of 0.2 W/m K. The ambient air temperature was assumed to 15 °C. The ground temperature was assumed to 10 °C.

The heat loss of different systems in different scenarios were investigated. For the system with micro tank, the heat loss mainly refers to the heat loss of the tank. The heat loss coefficient of the tank was referenced from the Danish standard [6], which should be no larger than 0.35 W/ m2 K. For the direct electric heater system with bypass function, the heat loss mainly includes the heat loss generated by bypass. The set-point temperature of the bypass was assumed to be 5 °C lower than the supply temperature of ULTDH.

The heat loss of the micro tank therefore can be calculated as:

$$Q_{tank} = q_{tank} * s * (t_{tank} - t_{amb}) \qquad (5)$$

where
q is the heat loss coefficient of the tank [W/ m2 K],
s is the surface area of the tank [m2].
The heat loss of the service pipe caused by bypass function can be calculated as:

$$Q_{tank} = q_{pipe} * (t_{pipe} - t_{ground}) \qquad (6)$$

where
q_pipe is the heat loss coefficient of the service pipe [W/ m K],
t_pipe is the average pipe temperature when bypass is operated [°C],
t_ground is the ground temperature [°C].

One thing should be pointed out is that the heat loss of the micro tank is covered by both heat and electricity. Considering the different primary energy factor, the proportion of different energy used for heat loss covering is equivalent to the proportion for water heating.

As an important parameter, the return temperature to DH was also investigated for the three configurations. For the micro tank system, since no bypass was operated, the average return temperature is the return temperature for water heating. While for the direct electric heater system, it was calculated as the volume-based average return temperature, which integrated the water heating flow and bypass flow.

The volume-averaged return temperature can be calculated as:

$$\overline{t_{ret}} = (t_{wr} * v_w + t_{br} * v_b) \qquad (7)$$

where
t_wr is the return temperature for water heating [°C],

v_w is the flow for water heating [L/day],

t_br is the average temperature of the service pipe when bypass is operated [°C],

v_b is the flow for bypass [L/day].

4. Results

4.1. Dimension of the micro tank for different scenarios

The dimensions of the micro tank on the primary side with different ULTDH supply temperature are shown in Table 4.

Table 4 Dimension of the micro tank on the consumer side with supply temperature at 35 °C, 40°C, and 45 °C.

	Supply temperature of ULTDH		
	35 °C	40 °C	45 °C
V_a [L]	21.5	14.4	3.8
P_{max}^a [kW]	2.3	1.3	0.3
V_{extra} [L]	2.5	0	0
Tank size [L]	25	15	5

As shown in the table, the scenario with supply temperature at 35 °C is the only scenario that required power of the electric heater larger than 2 kW. As a result, it is the only scenario requires extra volume for the tank.

In terms of the micro tank on the primary side, the results are shown in Table 5.

Table 5 Dimension of the micro tank on the primary side with supply temperature at 35 °C, 40°C, and 45 °C.

	Supply temperature of ULTDH		
	35 °C	40 °C	45 °C
V_a [L]		57.2	
P_{max}^a [kW]	3.0	3.0	3.0
V_{extra} [L]	76.3	76.3	76.3
Tank size [L]	80	80	80

All the tank sizes were made to approach the closest existing product.

Comparing the results from Table 4 and Table 5, the micro tank on the primary side requires much larger dimension with the same ULTDH supply temperature, which can increase the investment cost.

4.2. Comparisons of three configurations

The heat losses of the three configurations are calculated. The results of considering / without considering the primary energy factor (2.5 for electricity) are shown in the following diagrams.
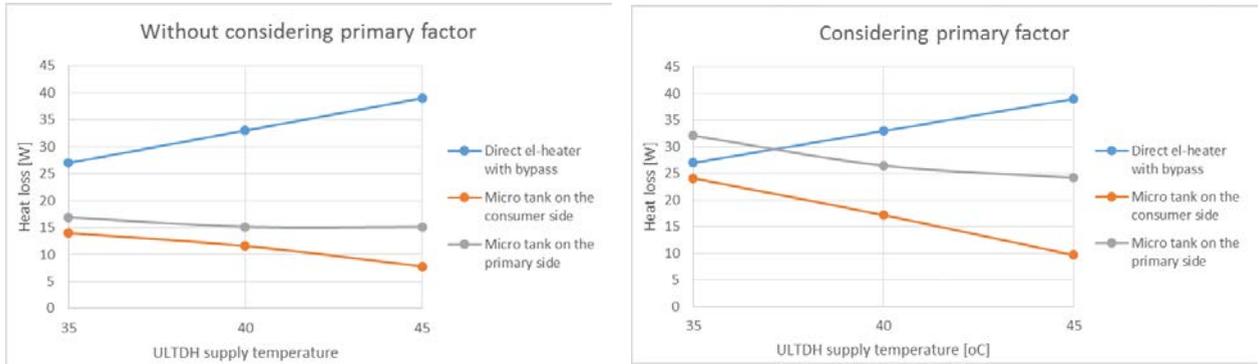
Fig. 6 **(a)** Without considering the primary energy factor; (b) Considering the primary energy factor of 2.5 for electricity

Heat losses for three DHW configurations with different ULTDH supply temperatures

From Figure 6 (a), without considering the primary energy factor, the heat losses of the micro tanks systems are much less than the direct electric heater system with bypass. However, the trends along the temperature increase are different. The heat loss caused by bypass increases if the ULTDH supply temperature is higher. While for the micro tank system, the tank size is smaller if the supply temperature is higher. Moreover, the proportion of the electricity consumption in covering the heat losses also decreases with higher supply temperature.

If taking the 2.5 primary energy factor for electricity into account, the system with a micro tank on the primary side has the largest heat loss when the supply temperature of ULTDH is lower than 37 °C. After that, the heat loss of the direct electric heater system with bypass becomes the largest. The system with a micro tank on the consumer side always has the lowest heat loss.

The results of the average return temperature of the direct electric heater system with bypass are shown in Table 6

Table 6 Dimension of the micro tank on the primary side with supply temperature at 35 °C, 40°C, and 45 °C.

	Supply temperature of ULTDH		
	35 °C	40 °C	45 °C
Set-point temperature of bypass [°C]	30	35	40
Water-heating flow [L/day]	127.2	121.5	117.9
Bypass flow [L/day]	111.1	135.8	160.5
Average return temperature [°C]	24.0	27.4	31.0

From the results, by mixing the bypass flow, the average return temperatures of the direct electric heater system increase significantly. Compared to the micro tank system, the average return temperature increases by 5.2 °C, 8.6 °C, and 12.2 °C with the supply temperature at 35 °C, 40 °C, and 45 °C.

5. Discussion

The return temperature plays an important role in improving the energy efficiency of the DH system. The influence of the DHW configuration was discussed in this study, however, to obtain full knowledge about it, the

analyses for the space heating loop should be taken into account. Further information regarding to the impact by the space heating loop can be found in [7]. In addition, the room temperature of the substation also plays a role in the heat loss from the distribution pipes inside the building, which can influence the average return temperature of DH system. In this study, the room temperature of the substation was assumed to 15 °C all the year. However, in reality this temperature can be varied, the impact of which should be taken into account for the analysis of DH return temperature in the future.

As shown in the results, the operation of bypass can increase the average return temperature substantially, which makes conflict for improving the overall efficiency of the ULTDH system. In Denmark, if the average return temperature to district heating is below 42.9 °C, for every 1 °C reduction further, the overall cost for heat supply can reduce by 1%. According to the results of this study, it means the total cost for heat supply can save up to 12.2% if replacing the bypass by applying the micro tank solution. However, the actual savings should be analysed according to specific cases, since the results can be affected by many practical factors. Moreover, to target the appropriate DHW configuration, the economy of each system, the installation difficulty and etc. should also be taken into account in the future.

6. Conclusion

In this study, long-term measurements were performed in two Danish houses with ULTDH supply. The performances of the DHW configurations were investigated accordingly. The house with direct electric heater had lower return temperature compared with the house with storage tank. The difference of the return temperatures was 7.8 °C in winter and 5.8 °C in summer.

To improve the electric heater system, system with a micro tank with immersion heater was devised to eliminate the bypass function. Depending on the location of the tank, two types of micro tank systems were invented. The heat losses of the micro tank systems were compare to the direct electric heater system with bypass under standard condition. Considering the primary energy factor of 2.5 for electricity, the heat loss of the direct electric heater system was larger than the micro tank systems when the ULTDH supply temperature is higher. The system with a micro tank on the consumer side had the lowest heat loss. Moreover, the micro tank system also achieved significant reduction on the average return temperature by avoiding the bypass.

7. Acknowledgement

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