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Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating

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A B S T R A C T

This study investigated the performances of five different substation configurations in single-family houses supplied with ULTDH (ultra-low-temperature district heating). The temperature at the heat plant is 46 °C and around 40 °C at the substations. To avoid the proliferation of Legionella in the DHW (domestic hot water) and assure the comfortable temperature, all substations were installed with supplementary heating devices. Detailed measurements were taken in the substations, including the electricity demand of the supplementary heating devices. To compare the energy and economic performance of the substations, separate models were built based on standard assumptions. The relative heat and electricity delivered for preparing DHW were calculated. The results showed that substations with storage tanks and heat pumps have high relative electricity demand, which leads to higher integrated costs considering both heat and electricity for DHW preparation. The substations with in-line electric heaters have low relative electricity usage because very little heat is lost due to the instantaneous DHW preparation. Accordingly, the substations with in-line electric heaters would have the lowest energy cost for DHW preparation. To achieve optimal design and operation for the ULTDH substation, the electricity peak loads of the in-line electric heaters were analysed according to different DHW-heating strategies.

1. Introduction

1.1. Temperatures of DH (district heating) and DHW (domestic hot water)

District heating is a cost-efficient way of supplying heat to consumers, especially in regions with high heat density. After decades of development, district heating is now transiting from medium-temperature district heating to LTDH (low-temperature district heating). From a macroscopic point of view, low-temperature levels bring many benefits to a district heating system. Low-temperature district heating system is an integrated part of the future sustainable energy systems, which aims at better utilizing the renewable energy sources, such as the geothermal energy, solar thermal energy, or industrial excessive heat, waste incineration and etc., and phasing out the fossil fuels. With developed technologies and operation methods, low-temperature district heating system is able to achieve low distribution heat losses by integrating with heat storage. To achieve low supply temperature without changing the DH system dimension and weaken the DH system efficiency, more efficient cooling is required to reduce the return temperature. The more efficient cooling of the DH flow can be achieved by better operation of the heating system, well designed and controlled radiators for space heating, more effective heat exchangers for DHW and etc. One benefits by the low distribution temperatures is the savings of the heat loss in the district heating grid [1]. Moreover, Low return temperatures can increase heat recovery through flue gas condensation. According to the definition of 4th generation district heating [2], LTDH can achieve supply and return temperatures of 50 °C/20 °C without violating comfort and hygiene requirements.

The aim of applying ULTDH (ultra-low-temperature district heating) is to make the utmost use of available low-temperature heat sources and to achieve both energy savings and economic feasibility when supplying heat to consumers. The supply temperature of ULTDH is lower than that of LTDH (50 °C), but has not yet been clearly defined. To meet comfort and hygiene requirements, ULTDH can be used in combination with local supplementary heating devices. However, it is better to have sufficient ULTDH supply temperature for space heating to provide a

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Nomenclature

c	Specific heat capacity of water [kJ/kg °C]
CRF	Capital recovery factor [%]
C_{inv}	Investment cost, [DKK/unit]
$C_{O\&M}$	Operation and maintenance cost [DKK/year]
E	DHW peak load in the substation [kW]
E_s	DHW peak load from the standard [kW]
i	Interest rate [%]
LC	Levelized cost [DKK/kWh]
$\dot{m}$	Flowrate of the water [kg/s]
n	Life time [year]
P_{dh}	Price of DH heat [DKK/kWh]
P_{el}	Price of electricity, [DKK/kWh]
P_{int}	Integrated energy price considering the DH and electricity [DKK/kWh]
q	Transient energy flow [kW]
Q_{dh}	Heat from district heating for DHW preparation [kWh]
Q_{dhw}	The increased energy content of the DHW [kWh]
Q_{dhw_y}	Annual DHW demand [kWh]
Q_{el}	Electricity demand of the supplementary heating devices for DHW preparation [kWh]
Q_{hl}	Heat loss of the DHW preparation process [kWh]
Q_{input}	Total energy input to the substation [kWh]
Q_{output}	Total energy output from the substation [kWh]
t_{dcw}	Temperature of the domestic cold water [°C]
t_{dh_s}	Supply temperature of DH [°C]
t_{dh_r}	Return temperature of DH [°C]
t_{el}	DHW temperature heated by electricity [°C]
t_{in}	Inlet temperature of the water flow [°C]
t_m	DHW temperature preheated by district heating [°C]
t_{out}	Outlet temperature of the water flow [°C]
Greek	
ε_{dh}	Relative heat demand for DHW preparation [%]
ε_{el}	Relative electricity demand for DHW preparation [%]
φ_k	Volume percentage of DHW for kitchen use [%]
Abbreviations	
COP	Coefficient of performance
DCW	Domestic cold water
DH	District heating
DHW	Domestic hot water
LTDH	Low-temperature district heating
ULTDH	Ultra-low-temperature district heating
Numbers	
1–5	Substation #1–5

comfortable indoor temperature, so that extra investment costs for space heating can be avoided. With efficient operation and space-heating devices, a supply temperature above 40 °C is sufficient to provide comfortable room temperatures during the heating season. In terms of supply temperature for DHW, auxiliary heating devices are needed to reach 45 °C for kitchen use and 40 °C for other uses based on the requirement for comfort [3].

1.2. Concern about Legionella in the DHW system

Prevention of Legionella in DHW systems plays a very important role in the design and operation for DH substations. Several previous studies [4–6] have indicated that favourable conditions for Legionella's proliferation are: 1) water temperatures ranging from 25 to 45 °C, and 2) long-term stagnancy. The problem of Legionella in DHW systems clearly needs to be addressed in advance of the realization of LTDH and ULTDH. One approach could be to add local supplementary heating devices, so that the temperature of DHW can be boosted. Another method is to limit the total volume of DHW in use and heat the DHW locally and instantaneously, thereby reducing the risk of stagnancy as much as possible. The operation requirements of DHW installations depend on their layouts. For example, in Denmark the standard [7] for Legionella prevention requires that no point in a DHW system with circulation should have a water temperature lower than 50 °C, and it should be possible to heat the water in the tank up to 60 °C. But if the DHW system has no circulation and or water storage, there are no requirements for the temperature beyond those for comfort.

1.3. The performances of different substations

Different substations have different layouts and operation modes, which have great influence on the efficiency of DHW preparation and distribution. Bøhm [8] measured DHW systems in 13 apartments and 2 institutes in Denmark, and found that circulation systems have very low efficiency. By removing the circulation pipe and adding electric heat tracing to the supply pipe, he found that both the district heating return temperature and the pipe heat loss could be reduced. Cholewa et al. [9], made experimental measurements and found that residential thermal stations have better annual average efficiency than centralized heating systems when supplying both space heating and DHW. Boait et al. [10] report test results for five different DHW heating systems with five heating appliances in the UK. They found that instantaneous preparation of hot water is much more efficient than systems with storage tanks, as well as more effective in preventing Legionella. A simulation study made by Basciotti et al. [11], compared different types of substations with LTDH supply. Their results indicate that the instantaneous preparation of DHW at 50 °C using a heat pump results in lower district heating return temperatures, while a system with an air source heat pump as auxiliary heater and storing hot water at 60 °C has the lowest primary energy demand. In addition to the selection of appropriate substations for specific cases, fault detection also plays a role in ensuring the correct operation and good performance of the substation. In Gadd and Werner's work [12], the frequency of annual temperature difference faults in substations is more than 6%, and they are difficult to detect and eliminate because of the irregular heat demand pattern and intensive labour cost. This means it is of great importance to have a reference indicator that can evaluate the operation and performance of the substation, thereby improving efficiency on both the consumer side and the supply side.

1.4. The scope of this study

Very little research has been done on the performance of substations with ULTDH. The aim of this study is to provide comprehensive analysis based on both empirical data and models of various substations with ULTDH supply. We made detailed measurements in five single-family houses with ULTDH supply. Since the five houses all have different supplementary heating devices for DHW preparation, we built five models to simulate the DHW