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Computational and experimental performance analysis of a novel method for heating of domestic hot water with a ground source heat pump system

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ABSTRACT

The paper presents a novel method developed for energy efficient heating of domestic hot water (DHW) with a ground source heat pump (GSHP) system. The method is based on step-based heating of DHW, where the DHW is gradually heated from the inlet temperature of domestic cold water to the target temperature of DHW using a specifically designed GSHP system concept. The developed method was tested and validated using experimental and computational performance analyses and the energy efficiency, operation and potential limitations of the developed application were also studied in existing apartment buildings. To demonstrate the efficiency of the developed application, the performance of the new concept was compared to the performance of a conventionally used GSHP system. The results demonstrated that the developed GSHP concept delivered up to 45–50% improvement in energy efficiency of the DHW heating process over the conventional GSHP application. The measured Seasonal Performance Factors were 2.5–2.6 for the conventional application and as high as 3.7–3.8 for the developed application, when DHW was heated from 7.5 °C to 55 °C. The case study demonstrated that the developed concept is also well applicable in existing buildings, but there is still room for improvement.

1. Introduction

The recast Energy Performance of Buildings –directive (EPBD) requires that all new buildings must be nearly zero-energy buildings (nZEBs) by the end of 2020 [1]. While the detailed country-specific definitions of nZEBs are left to the Member States of the European Union, the recast EPBD requires nZEBs to be buildings with high energy performance and that renewable energy sources (RES) are effectively utilized to cover the primary energy (PE) demand of nZEBs [1]. Recent studies demonstrate that heat pump systems, especially a ground source heat pump (GSHP) system, are one of the best applications to utilize RES and to improve the primary energy performance of buildings cost-effectively, depending on the Member State-specific PE factors [2–7]. The popularity of heat pump installations is also increasing in deep renovations of buildings, as the heat pump systems typically provide a cost-effective alternative to significantly improve the energy efficiency of a building over the more conventional renovation measures related to improving the energy efficiency of the building envelope [2,3,8,9].

Heating of domestic hot water (DHW) accounts for a significant share of the overall energy consumption in residential buildings. According to a study conducted by Yao and Steemers [10], up to 20% of the overall domestic energy is used for DHW purposes in the United Kingdom. The DHW consumption of residential buildings accounts for as high as 72% of the total DHW consumption [11]. A literature review conducted by Ahmed et al. [12] indicated that the DHW consumption due to occupants fluctuates significantly from country to country, but an average consumption is typically 30–70 L/person/day. Ahmed et al. [12] also concluded that the season of the year affects the DHW consumption rate so that more

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DHW is consumed during the winter time and less during the summer time, respectively. According to their study, the specific DHW consumption of smaller apartments with 1–2 occupants is approximately 1.5 times higher than the specific DHW consumption of larger apartments in Finnish residential apartment buildings.

In many European countries, a significant share of the population lives in multi-family apartment buildings, where the heating of DHW can account for more than 50% of the overall heating energy demand of the building, depending on the age, size, location and energy performance of the building [5,13–16]. In Nordic countries, the average DHW consumption rate is approximately 35 L/person/day with the highest consumption rate occurring in Finland (43 L/person/day) and the lowest occurring in Denmark (20 L/person/day) [12]. For comparison, Swan et al. [17] have determined that the average DHW consumption of typical Canadian households is approximately 67 L/person/day. This indicates that energy efficient heating of DHW has a significant impact on the overall energy performance of future nearly zero-energy apartment buildings, where the energy efficiencies of the building envelope and technical systems of the building are already maximized or at a high level.

Several studies have investigated the performance, energy saving potential and operation of GSHP systems in different climate conditions and concluded that the GSHP system is typically a highly efficient energy production technology in many different applications and building types, when cost-effectiveness, energy efficiency and environmental impact aspects are taken into account [18–24]. While the technology development of the GSHP systems has improved the energy performance, operational characteristics, reliability and controllability of the systems, the overall energy efficiency of a GSHP system is still highly dependent on the temperature levels of both the evaporator and the condenser. It has been concluded in numerous previous studies that energy efficient heating of DHW is the major challenge related to the performance of the GSHP systems especially in cold climate conditions, as the temperature requirement of DHW is typically 55–60 °C to prevent legionella growth [2,5,8,18,25–27]. The coefficient of performance (COP) of conventional GSHP systems is typically in the range of 2.2–3.0, when DHW with the aforementioned temperature requirement of 55–60 °C is produced and the inlet temperature of domestic cold water (DCW) is 5–10 °C, respectively.

The literature review related to GSHP applications in energy efficient and nearly zero-energy residential buildings indicates that cost-efficient, operational and implementable applications are required to improve the energy efficiency of DHW heating with the GSHP systems, as the heating of DHW accounts for a significant share of the overall energy consumption in new, deeply renovated and future nearly zero-energy residential buildings. The literature review also indicates that there is a limited number of studies related to investigating and improving the efficiency of heat pump system applications operating in multi-family residential buildings. In addition, majority of the previous studies [28–33] have focused on studying solar assisted GSHP applications, which may not be the cost-optimal GSHP system application in many of the apartment building cases due to the main limitations related to the solar thermal systems, such as a limited roof area in large high-rise apartment buildings and increased technical space requirements for installation of accumulators or heat storages.

This study presents a novel method developed for energy efficient heating of DHW with a GSHP system in multi-family apartment buildings without the need for auxiliary heating systems or supporting renewable energy production systems, such as a solar thermal collector system. The performance of the developed method is studied and validated by computational and experimental analyses and also by conducting on-site field studies in existing apartment buildings located in the cold climate of Finland. The efficiency of the developed method is also compared to the efficiency of a conventional method applied for heating of DHW with a GSHP system to determine the improvements in energy performance. As a result of the computational validation analysis, an energy simulation model is developed to simulate the performance and operation of a GSHP system utilizing the developed DHW heating method. The simulation model can be further developed to optimize the performance of GSHP systems according to local electricity spot-prices, case-specific DHW consumption profiles or cost-optimal demand response strategies. The objectives of this study are:

- to study and validate the performance of a novel method developed for energy efficient heating of DHW with a GSHP system in multi-family apartment buildings;
- to compare the efficiency of the developed method to the efficiency of a conventional and typically used application for heating of DHW with a GSHP system;
- to determine the difference in energy efficiency between the developed and the conventional GSHP DHW heating applications;
- to develop and validate an energy simulation model for performance assessment and optimization of GSHP systems utilizing the developed method;
- to study the performance, functionality and potential limitations of the developed method in existing apartment buildings located in cold climate conditions.

2. Methods

2.1. Heating of DHW with geothermal heat pump systems

2.1.1. Thermodynamic principle

This study focuses on developing a new method for energy efficient heating of DHW with a GSHP system in multi-family apartment buildings. The method can also be utilized in non-residential buildings and with other heat pump types in addition to the GSHP, e.g. air-to-water, exhaust air and hybrid heat pumps. The method is based on step-based heating of DHW, where the heating of DHW is started from the inlet temperature of DCW, e.g. 5–10 °C. In the step-based heating method, the DCW is gradually heated to the target temperature of DHW, e.g. 55 °C, whereas in majority of the conventional DHW heating applications utilizing a GSHP system, the DCW is heated to the required temperature of DHW in a separate heat storage tank or in a combined heat storage tank used for space (and ventilation) heating and DHW. The conventional heating method requires that the heat storage tank used for heating of DHW must be at a high temperature, e.g. 60–65 °C, at all times to prevent legionella growth [34], which reduces the COP of the heat pump system significantly compared to a situation, where the DCW is heated to the required temperature of DHW in several steps.

The basic thermodynamic principle of a five-step heating process of DHW using the R410A refrigerant, a commonly used refrigerant in modern commercially manufactured GSHP systems, is presented in Fig. 1 [35]. The data presented in Fig. 1 is calculated using the thermodynamic properties of the R410A refrigerant. The heating of DHW from 5 °C to 55 °C is divided into 5 steps, which improves the overall COP of the heating process, as the condensing pressure of R410A is significantly lower at low condensing temperatures and increases exponentially, when the condensing temperature increases (see Fig. 1). By dividing the heating of DHW into multiple steps, the average condensing pressure of the overall heating process decreases, thus improving the energy performance of the heat pump system significantly compared to the situation, where the heat pump system maintains 60–65 °C temperatures in the heat storage tank at all times in order to supply 55 °C DHW to occupants. The average condensing pressure of the five-step