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Exergy analysis of a hybrid ground-source heat pump system

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HIGHLIGHTS

- Detailed thermodynamic analysis of individual components of a hybrid GSHP system.
- Comparison of heating and cooling mode highlights importance of a low temperature spread.
- Use of the natural energy source is significantly more efficient in cooling mode.
- Analysis of different strategies to increase the exergy efficiency of the system.
- Reduction of energy demand is shown to be more effective than operational system changes.

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ABSTRACT

In contrast to energy analysis, the analysis of exergy allows the evaluation of the quality of different energy flows and enables a comprehensive assessment of inefficiencies within a system and its individual components by accounting for exergy consumption. While exergy analysis methods have been applied to a variety of conventional and renewable energy supply systems, there is still a lack of knowledge regarding the exergy flows and exergy efficiency of hybrid ground-source heat pump systems with a supplementary boiler. In this study, we develop a thermodynamic model for each subsystem in a hybrid heating and cooling system of an existing building by applying the concept of cool and warm exergy. A comparison of the exergy consumption of the hybrid system in heating and cooling reveals that there are significant differences regarding the components that attribute most to the overall exergy consumption in the system. Due to these differences the true exergy performance of the system in heating mode (~30%) is twice as high as for cooling mode (~15%), while the natural exergy performance is considerably better in cooling mode (~26% to ~3%). Potential measures to enhance the exergy performance based on changes in the operational settings of the system and the improvement of the building envelope were found to have a more significant effect on heating performance than on cooling performance. In general, measures that affect the amount of thermal energy delivered by the system appear to be more effective than changes to the operational settings of energy supply systems.

1. Introduction

In thermodynamics, the exergy content of a system is defined as the maximum theoretical amount of work that can be extracted from this system in relation to a certain reference state, which usually refers to temperature conditions outside of the investigated system [1]. The analysis of exergy contents and flows offers a concept to assess the quality of energy, which has been applied in various fields of energy research, such as utilization and storage of energy [2–4], renewable and sustainable energy technologies [5–9] and energy processes [10–13]. The analysis of exergy (or 2nd law analysis) quantifies the quality of different energy flows through a system and so enables a comprehensive assessment of all important aspects of energy utilisation [14]. In addition, exergy consumption, which represents a reduction in the ability of the system to deliver thermal energy, can be quantified on a detailed level for individual subsystems of energy supply systems and thus enable a more thorough examination of system efficiency than energy analysis [15]. Furthermore, by applying exergy analysis

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Nomenclature

Variables
- c specific heat capacity [kJ/(kg K)]
- E power consumption [kW]
- HX_{eff} effectiveness of the heat exchanger [–]
- k irreversibility factor [–]
- m mass flow rate [kg/s]
- Q energy [kW]
- r ratio of chemical exergy for natural gas [–]
- T temperature [K]
- X exergy [kW]
- η efficiency [–]

Subscripts
- 0 reference (outdoor) condition
- b geothermal circulation fluid, borehole heat exchanger
- *boiler* boiler
- c condenser of the heat pump
- *ceil* consumption at the ceiling
- *comp* compressor of the heat pump
- *cond* consumption at the condenser
- *CP* main circulation loop
- *divHP* diverted heat pump loop
- *divHX* diverted heat exchanger loop
- e evaporator of the heat pump
- *evap* consumption at the evaporator
- g ground
- *gex* consumption at the borehole heat exchanger
- *HP* heat pump
- *HX* heat exchanger
- *HXload* load side of the heat exchanger
- *HXpump* boiler (heat exchanger source side) loop circulation pump
- *HXsource* source side of the heat exchanger
- *in* system/component inlet
- *ind* indoor
- *load* load side of component
- *loss* consumption due to imperfect heat exchange
- *mix* mixing valve after heat pump (HP) or heat exchanger (HX)
- *NG* natural gas
- *out* component/system outlet
- *power* electricity input
- *pump* ground loop circulation pump
- *re* return, i.e. system/component inlet
- *refcycle* consumption in the refrigerant cycle
- *source* source side of component
- *sup* supply, i.e. system outlet
- *tot* total efficiency/input
- *transfer* consumption during heat exchange
- *val* consumption in the mixing valves
- w heating/cooling fluid
- *wb* boiler loop fluid

the magnitude and location of thermodynamic imperfections can be identified. Thus, exergy analysis methods are also ideal when system improvement is needed [16].

With a large amount of energy being used for space heating and cooling there has been an increasing interest in applying exergy analysis to understand the overall utility of energy supply systems with the aim of optimizing efficiency [17–20]. Several recent studies used exergy analysis for the evaluation of operation and control strategies of conventional HVAC systems [21–24], while other studies compared the overall energy and exergy performance of such systems under different climatic conditions and for different reference states [25–29]. With the increasing use of renewable energy technologies for space heating, recent years have seen a large amount of work on the exergetic evaluation of ground (GSHP), solar and air-sourced (ASHP) heat pump systems [30–34]. These studies have shown that systems using renewable energy sources are typically favourable with regard to exergy performance, when combined with a moderate temperature heating systems, such as radiant floor or wall-mounted systems [35]. This is due to the low temperature spread between heat source and supply system, which results in lower entropy generation and consequently in lower exergy consumption [36,37]. Evaluation of water-based systems for space cooling that employ renewable energy source, on the other hand, can be found less frequently in literature [38,39], and studies investigating systems for both space heating and cooling from one system are still rare [40,41].

Also, recent developments and increasing popularity of hybrid GSHP systems with additional heat sources or sinks are not yet reflected in available methods for exergy analysis of such systems [42,43]. So far, only three studies investigated the exergy flows and efficiencies for a GSHP system with additional heat sinks, such as a cooling tower or a crawl-space below a residential building [29,39,44]. However, to our knowledge no study has investigated the exergetic performance of a GSHP system with a supplementary, gas-fired boiler, although this type of system is becoming increasingly popular due to lower installation and operational costs [45]. The introduction of a boiler component to the low or moderate temperature system will be interesting, as such a high-temperature component has the potential to significantly affect the exergy efficiency and consumption in the system. Consequently, the performance of such a hybrid system might also differ significantly in heating and cooling mode.

Such a detailed investigation requires a detailed analysis on the level of individual system components, which was so far conducted only by Li et al. [38] for a GSHP and ASHP system in cooling mode. In addition, comparing the performance of the system in heating and cooling mode in detail also requires taking into account the different types of exergy, warm and cool, and thus a more complex analysis than the standard approach followed by the vast majority of existing studies. Indeed, a recent review on GSHP systems highlighted the benefits of detailed, analytical exergy analysis to identify irreversibilities at different locations in the system, and concluded that further improvements of this method offer a large potential to enhance the efficiency of GHSP systems [46].

To address the research gaps highlighted above, we carry out a detailed exergy analysis of a hybrid system with a supplementary boiler operating in both heating and cooling modes. To do so, we develop a comprehensive and novel thermodynamic model comprising of all technical components under consideration of warm and cool exergy. The thermodynamic model constitutes new formulations for the energy and exergy terms for the subsystems relating to the supplementary boiler, such as the heat exchanger and the mixing valves. We assess exergy efficiency at different levels and according to the different energy and exergy sources, such as natural and non-natural exergy, to allow a detailed comparison of different aspects of system performance in different operational modes. To demonstrate the application of exergy analysis to real systems in the context of system design and management, we investigate three different hypothetical scenarios for potential improvement of the performance of the hybrid system relating to changes in equipment, operational strategies and building envelope improvements. In addition this scenario analysis will