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Impact of ventilation rates on indoor thermal comfort and energy efficiency of ground-source heat pump system

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ABSTRACT

The ground source heat pump (GSHP) is currently employed to improve the overall energy efficiency of the building sector. Many studies have been directed to optimizing the energy efficiency (GSHP) through its source side. The potential influence of air side of GSHP on the energy efficiency is not fully addressed. Yet, ventilation of the GSHP serves as a hub linking indoor thermal comfort and power consumption together. In this paper, we present a systematic study focusing on the ventilation rate of the GSHP system from the perspective of energy saving and indoor thermal comfort combined. This study constructed the mathematical model of PMV (Predicted Mean Vote) and power connected by ventilation rate through a full-scale GSHP system. The results have indicated that the system COP is significantly influenced by the ventilation rate changing from 4 to 2.1. The non-linear decrease of the coefficient of performance (COP) creates a turning point in the PMV ~ power demand curve of the GSHP system, where the lowest power demand can be achieved at a 0.33 ventilation rate fraction while PMV level is improved from 'slightly warm' to 'nearly neutral'. Finally, the study constructed different scenarios considering different ventilation methods and different cooling capacities.

1. Introduction

The building sector is under pressure to improve its overall energy efficiency due to its colossal energy demand. As in China, the building sector represents 46.7% of the total primary energy use and 60% of the total carbon emission (Li, Yang, He, & Zhao, 2014; Zhang, He, Tang, & Wei, 2015). In this context, one of the main strategies to reduce the energy intensity of buildings is to use the decentralized renewable energy systems such as the ground-source heat pump (GSHP) (Kim & Baldini, 2016; Kim, Leibundgut, & Choi, 2014). The GSHP system utilizes low depth soil as a heat source or sink. Thanks to the relatively stable soil temperature, the coefficient of performance (COP) of the GSHP system is significantly higher than conventional air conditioner (Huang & Mauerhofer, 2016; Zhang and Zhang et al., 2017). It is reported that the COP of GSHP system can reach the range of 4–5 (Zhang and Zhang et al., 2017), while the traditional air conditioner is operated in the level of 1.6 ~ 2. The large integration of the GSHP system for buildings and districts heating is therefore considered to be one of the main strategies to lower energy demand of buildings and realise a sustainable society (Abdurafikov et al., 2017). With these advantages, GSHP installations in China have seen a significant increase since 2005 with a growth rate exceeding 60%. By comparison, the average growth rate of GSHP applications in the world is only recorded at 20% (Liu, Lu, Hughes, & Cai, 2015). In 2014, China achieved the first place in the world regarding the direct utilization of geothermal energy reaching 17870 MWt (Zhu et al., 2015).

Though the GSHP system has higher energy efficiency potential, continuous efforts are still needed to guide its design and configuration to fully explore the benefit. As summarised in ref., the influencing parameters on the COP of a GSHP system can be categorized into four groups: ground properties, borehole heat exchanger, heat pump operating parameters and ventilation system (Sivasakthivel, Murugesan, & Sahoo, 2014). Numerous studies have been dedicated to the influences of the soil temperature change (Ikeda, Choi, & Ooka, 2017; Qian and Wang, 2014; Zhou, Cui, Li, & Liu), borehole arrangement (Dehghan, 2017; Kurevijaet al., 2017; Piscaglia et al., 2016; You et al., 2017; Zhou and Wu et al., 2016), and ground heat exchanger design (eg., cross-section design (Kong, Deng, Li, Gong, & Cao, 2017) or ground heat exchanger material (Cao et al., 2017) etc.) (Cao et al., 2017; Hein et al., 2016; Kong et al., 2017). The heat pump operating parameters including different combinations of inlet/outlet temperatures from condenser and evaporator are carefully examined in the literature (Pandeyet al., 2017) to identify an optimal COP level. To the authors' knowledge, few studies are dedicated to the potential impacts of the ventilation system. However, the ventilation system of the GSHP system may be critical since it connects indoor thermal comfort and energy

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consumption. Since people spend around 90% of time conducting indoor activities (McGrath et al., 2017), it is essential to provide a healthy and thermal-comfortable indoor living environments (Jamaludinet al., 2015). The indoor thermal comfort condition can significantly affect health (e.g., the sick building symptom) and productivity of the building occupants (Shan, Zhou, Chang, & Yang, 2016). To measure the extent of indoor thermal comfort, the predicted mean vote (PMV) indicator has been developed involving air temperature and velocity (Hasan, Alsaleem, & Rafaie, 2016). Both parameters are directly influenced by ventilation of the GSHP system. Meanwhile, the indoor thermal comfort is closely connected with the building energy demand since heating, ventilation, and air conditioning system (HVAC) contributes to 30–60% of total energy use by buildings (Kwong, Adam, & Sahari, 2014). In this regard, a therma.comfort level acts as boundaries to define to what extent buildings should be heated or cooled.

As for the conventional HVAC system, studies on its energy savings with a constraint of maintaining a certain PMV level have been widely documented (Dounis and Caraiscos, 2009; D'Oca, Hong, & Langevin, 2018; Kanet al., 2015; Pombeiro, Machado, & Silva, 2017; Ruppet al., 2015; Shaikhet al., 2014; Xu, Hu, Spanos, & Schiavon, 2017). The first branch of the research focuses on optimizing the control mechanisms of the air conditioning system. The intelligent control mechanisms such as the model predictive control (MPC) (Cauchi et al., 2017; Ku, Liaw, Tsai, & Liu, 2015; Mei and Xia, 2017; Oldewurtel et al., 2012) for the operation of air conditioning systems are intensively evaluated aiming to maintain comfortable indoor environment while improving their energy efficiencies. The intelligent control methods result in a sequence of set-point temperatures, which may be further modulated through fan speed, ventilation rate or compressor speed (Alamin, Castilla, Álvarez, & Ruano, 2017; Mei and Xia, 2017). Moreover, due to the fact that the thermal comfort is both influenced by air temperature and velocity, another branch of investigation aims to manipulate the air supply rate and room temperature combination for energy saving. It is known that 1 °C increase in room temperature can result in an average of 6% energy savings from the air conditioning system (Yamtraipat, Khedari, & Hirunlabh, 2005). Thus, a faster average room air velocity coupled with a higher room temperature setting generates similar PMV while reducing energy consumption. A very recent study calculates the energy consumption of different combinations of parameters including setpoint temperatures and air supply rates. They estimated a maximum 7.8% energy saving by fine-tuning the room air temperature and the corresponding average air velocity (Zhang, Cheng, Fang, Huan, & Lin, 2017). Moreover, measures for encouraging air flows in an air-conditioned environment for better individual thermal comfort have also been proposed and evaluated. By artificially increasing local air flows, the energy consumption from the air conditioner can be reduced with a similar PMV requirement (Schiavon and Melikov, 2008; Zhai, Arens, Elsworth, & Zhang, 2017).

After reviewing these studies on thermal comfort-oriented energy saving, we believe that current research should be further improved by focusing on its ventilation of the GSHP system. First, some studies (Yang and Wang, 2012, 2015; Zhang and Cheng et al., 2017), including popular building energy simulation software such as the Designbuilder, assign a single COP value for the different operating parameters to simplify the energy consumption estimate. However, for a GSHP system, when air supply rate is changed, the water loop temperatures at the user side of the compressor are expected to be altered accordingly due to different heat transfer coefficients between the fan and ambient environment, and thus delivers different cooling loads This resembles the situation that the HVAC system is being operated under the partial load while it is known that system COP will be lower in such a situation (Takagi, Asano, & Bando, 2016). In addition, ventilation is known to exert great impacts on the indoor environment from both thermal comfort and air quality perspective (Cao et al., 2016; Cheng, Lin, & Fong, 2015; Zhou et al., 2017). The air velocity is directly connected to the supply ventilation rate and changing the ventilation rate can indirectly changing the indoor air temperature. Hence, the ventilation system is a hub linking PMV with the energy consumption, which represents an unaddressed knowledge gap. Finally, in the MPC control, the system energy consumption is constructed based on the complex statistical methods such as the multilayer perceptron neural network (Kusiak, Xu, & Zhang, 2014), support vector regression model (Xi, Poo, & Chou, 2007) and fuzzy logic model (Afram and Janabi-Sharifi, 2014). Such statistically-based approaches cannot provide a systematic view of the physical correlation for the energy consumption of the air conditioning system and PMV.

The study is therefore conducted at the full-scale GSHP system at Soochow University, Jiangsu Province, to build a model revealing the potential influences of the air supply rate on energy saving together with a proper indoor thermal comfort. The Jiangsu Province has the most intensive GSHP installations in Southeast China mainly due to its climatic conditions. Most of Jiangsu has a humid subtropical climate and belongs to Hot-Summer-Cold-Winter zone (HSCW) according to Chinese climate classification (Zhang and Zhang et al., 2017). The air temperature in Jiangsu fluctuated considerably in a year. The daily average outdoor air temperature was about −1 to 4 °C in January and 26–29 °C in July, which means that summer cooling and winter heating are both needed in Jiangsu. The investigation contains monitoring the operating parameters of the GSHP and energy consumption with different ventilation rates. With the uncovered relations between the COP and thermal comfort, the final PMV oriented energy optimization can be proceeded and extended to other ventilation methods. Even though the experiment is carried out with our specific situation, i.e., using GSHP system, the findings are expected to have a broad interest and applicability by extending to other HVAC systems. The structure of the paper is organized as the following: In Section 2, the methodology for constructing the PMV ~ power model connected through the ventilation rate is presented along with the experiment setup. Then, Section 3 demonstrates experimental results required to estimate the parameters in the PMV ~ power model. In Section 4, the correlation of PMV ~ power correlation graph over the range of ventilation rate is deduced and the implication for GSHP system control is proposed.

2. Material and methods

The material and methods section consists of three-fold components. First, a general scheme for triangle correlations between ventilation, thermal comfort, and power consumption is presented. Subsequently, a mathematical model for the power of the GSHP and indoor thermal comfort is constructed. Finally, a full-scale experiment is conducted to supplement the parameters for the proposed mathematical model enabling a detailed PMV ~ power analysis for optimization.

Fig. 1 depicts the general structure of this paper to correlate the energy consumption together with the PMV. The status monitoring step logs the supply/return water temperatures for the user side of the compressor, the operational power of the GSHP system, measurements of indoor temperature and air velocity under different air supply rates. The energy-saving step can then be formulated through investigation on the PMV behavior in relation to the different power demand of the GSHP system alongside the changes of ventilation rate. Further detailed information on the research implementation is presented below.

2.1. Methodology

The indoor thermal comfort (Eq. (1)) can be determined from room air velocity and temperature through multiple regression based on ASHRAE 55–2013 (Zhang and Cheng et al., 2017). Eq. (1) does not include humidity since thermal comfort is much less sensitive to humidity compared to temperature and velocity (Hasan et al., 2016). With the assumption of the room temperature equal to the mean radiant temperature (Hasan et al., 2016; Walikewitz, Jänicke, Langner, Meier,