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Energy and exergy analysis of a ground source heat pump system for a public building in Wuhan, China under different control strategies

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ABSTRACT

This paper presents the energy and exergy studies of a ground source heat pump (GSHP) system for a public building in Wuhan, China under five different control strategies to improve the system performance. Original system was under manual operation with constant frequency heat pump, constant speed circulation pumps, and constant water flow rate. The five control strategies were: 1) Automatic ON/OFF control based on Building Load Ratio (BLR); 2) Optimum circulation flow rate control; 3) Optimum ON/OFF control with variable speed heat pump units; 4) Variable flow control by adjusting valve position; 5) Variable flow control by variable speed pumps. The results of the system exergy efficiency, exergy loss, COP, and energy consumption under different operation scenarios are presented. By comparing original operation with the best case (scenario five), it is found that during cooling and heating season, the system exergy efficiency was improved from 9.0% to 10.4% and from 6.1% to 6.9%; exergy loss dropped by 31% and 51%; COP increased from 3.2 to 3.7 and from 2.7 to 3.8; and energy consumption was reduced by 37% and 60%, respectively.

1. Introduction

Ground source heat pump systems become attractive with the emergence of global energy crisis and environmental problems. They utilize passive heat stored in the ground to provide heating, cooling and hot water to the buildings. In China, the development of GSHP technology started in the1980s and the GSHP industry has rapidly expanded since 2005. According to the Ministry of Housing and Urban-Rural Development [1], the number of GSHP projects in China exceeded 23,000 in the year 2012, with total implemented area of over 240 million m^2. In 2017, the “13th Five-Year” Plan on Development and Utilization of Geothermal Energy was published, which aimed at expanding 1.1 billion m^2 more area on geothermal energy utilization. It is expected that the total area for geothermal energy utilization will reach 1.6 billion m^2 in the year 2020 [2].

Exergy analysis deals with second law of thermodynamics, which is an effective tool to evaluate the performance and locate the irreversibilities of the thermal process. A number of papers have discussed the exergy efficiency of GSHP, experimentally and analytically. However, little researches have been done with exergy analysis on different control strategies. Therefore, this paper focuses on the exergy analysis on different control strategies for GSHP system, in order to fill the gap of the literature.

Some papers focus on exergy analysis of GSHPs under different applications [3–11]. For instance, Hepbasli and Balta [4] studied the performance on the exergy efficiency of a GSHP coupled with a radiator for residential application. Kang et al. [8] presented a study on the exergy analysis of a combined heating and power (CHP) and GSHP coupling system.

Other researches combined exergy analysis with energy and/or economic and environmental analysis [12–21]. For instance, Akbulut et al. [20] conducted exergoenvironmental and exergoeconomic analyses for a vertical type of GSHP wall cooling system and later performed energy, exergoenvironmental and exergoeconomic analysis on the heating system [21].

A few researchers have tried to optimize the performance of GSHP considering thermodynamic factors [22–25]. For instance, Sayyadi and Nejatolahi [23] presented a total revenue requirement (TRR) method to perform thermodynamic and thermoeconomic optimization of a cooling tower-assisted GSHP with 12 design variables. Huang et al. [24] present an entropy generation minimization

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Nomenclature

c_p	Specific heat of fluid (water), 4.182 kJ/kg K for hot water and 4.192 kJ/kg K for chilled water
CAP	Actual operating cooling capacity, kW
CAP_0	Design capacity of the heat pump unit at full load, kW
COP_{HP}	Coefficient of performance of the heat pump unit, dimensionless
COP_{system}	Coefficient of performance of the GSHP system, dimensionless
$Ex_{h,in}$	Exergy of enthalpy of the entering fluid, kJ
$Ex_{h,in1}$	Exergy of enthalpy of the entering fluid at the load side, kJ
$Ex_{h,in2}$	Exergy of enthalpy of the entering fluid at the source side, kJ
$Ex_{h,out}$	Exergy of enthalpy of the leaving fluid, kJ
$Ex_{h,out1}$	Exergy of enthalpy of the leaving fluid at the load side, kJ
$Ex_{h,out2}$	Exergy of enthalpy of the leaving fluid at the source side, kJ
Ex_{in}	Exergy of the entering fluid, kJ
Ex_{out}	Exergy of the leaving fluid, kJ
$Ex_{Q,AHU}$	Transfer rate of exergy of heat between AHU and the indoor air, kJ
$Ex_{Q,GHE}$	Transfer rate of exergy of heat between ground heat exchanger (GHE) and the ground, kJ
$LOAD_{actual}$	Actual building load, kW
m	Mass of the fluid, kg
$\dot{m}$	Operating flow rate, in kg/hr
$\dot{m}_0$	Design flow rate, in kg/hr
$\dot{m}_{load}$	Chilled/hot water flow rate, in kg/hr
$\dot{m}_{tank,0}$	Mass flow rate of the replenish water, kg/hr
$\dot{m}_{tank,in}$	Mass flow rate of the entering water, kg/hr
$\dot{m}_{tank,out}$	Mass flow rate of the leaving water, kg/hr
$\dot{m}_{tank,use}$	Mass flow rate of the supply water, kg/hr
P	Actual input power to the unit, kW
P_0	Input power under full load condition, kW
$\dot{Q}_{DHW}$	Load of the domestic hot water, kW
$\dot{Q}_{HP}$	Cooling/heating output of the heat pump, kW
$\dot{Q}_{load}$	System thermal load, kW
R_{PLR}	Correction factor related to PLR, dimensionless
R_T	Correction factor related to temperature, dimensionless
T_{in}	Entering fluid temperature, K
T_{lo}	Supply water temperature from the heat pump units, K
T_o	Reference temperature, K
T_{out}	Leaving fluid temperature, K
$T_{tank,0}$	Replenish water temperature, K
$T_{tank,in}$	Entering water temperature, K
$T_{tank,out}$	Leaving water temperature, K
$T_{tank,use}$	User side supply water temperature, K
W_{HP}	Electricity consumption of the heat pumps, kJ
$\dot{W}_{HP}$	Electricity input to the heat pumps, kW
$\dot{W}_{pump}$	Electricity input to the pumps, kW
$\dot{W}_{pump0}$	Design input power of the pump, kW
W_{total}	Total electricity consumption of the system, including HPs, pumps and fans, kJ
$\dot{W}_{total}$	Total power input to the system, including HPs, pumps and fans, kW

Greek symbols

ΔT	Temperature difference between the supply and return water, $\Delta T = 5\,^{\circ}C$
$\sum W_{fan}$	Total power input to the fans, kJ
$\sum W_{pump}$	Total power input to the pumps, kJ

Subscripts

1	Load side
2	Source side
HP	Heat pump

method for optimal design of vertical U-tube GHEs for GSHP on the borehole and pipe characteristics.

Only a few published papers discussed the energy efficiency on the control of GSHP [26–30]. For instance, Del Col et al. [28] used experimental data and a modeling procedure to study the energy efficiency in a GSHP with variable speed drives and show the importance of adjusting the mass flow rate of the heat-carrier fluids. Edwards and Finn [29] developed a control strategy to predict optimal water flow rates under part load operation for a single speed GSHP and a two speed GSHP. The energy efficiency increase due to optimal water flow rate control was found to be between 20% and 40%, comparing with nominal flow rate operation. Lucia et al. [31] concluded the following work to be considered for future research: (a) the optimization based on the transient performance of GSHP systems and not on the sole design condition; (b) the integration of irreversible thermodynamic optimization approach into the algorithms of control systems.

The literature review did not reveal publications about the application of both energy and exergy analysis to GSHP systems under different control strategies to optimize the performance of the whole system.

This paper presents the exergy analysis of a GSHP system for a public building in Wuhan, China. Five different control strategies were proposed to improve the performance of the GSHP system. The control strategies vary on different aspects such as time schedule, circulating water flow rates, and constant/variable-frequency heat pumps. The dynamic mathematical models were developed under TRNSYS environment. The hourly outdoor air temperature is used as the reference state. The results of the annual system exergy efficiency, exergy loss, COP and energy consumption under different operation scenarios are presented.

2. Description of the system

The GSHP project is for a public building located in Wuhan, with area of 2923.2 m^2. It is a three-story building, with one underground floor and two floors above the ground level. There is an indoor swimming pool, a fitness center, and a kitchen room on the underground floor. There are VIP conference rooms, a reception lobby, an exhibition hall, and a dining hall on the first floor. In addition, there are office rooms, a chess poker room, and food service rooms on the second floor. The system is equipped with two heat pump units that produce 7/12 °C cooling water in summer. In winter they produce 45/40 °C hot water for heating and 45 °C domestic hot water. Table 1 provides the major equipment list and their design characteristics.

Fig. 1 presents the schematic diagram of the GSHP system. The system is equipped with a hot water tank for hot water storage, and the hot water load in winter is 140 kW. The ground heat exchanger is composed of vertical double U-tubes in parallel that are buried in vertical boreholes. There are a total of 104 wells with interval of 5 m and diameter of 150 mm. The effective depth of the buried pipe is