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Performance evaluation and modeling of a hybrid cooling system combining a screw water chiller with a ground source heat pump in a building

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ABSTRACT

The performance of a hybrid cooling system that combines a screw water chiller with a ground source heat pump (GSHP) was measured and analyzed at various cooling loads. In addition, the hybrid cooling system in a building was modelled sophisticatedly using EnergyPlus and then validated with the measured data. The coefficient of performance of the GSHP was lower than that of a conventional chiller in the monitored building, but the hybrid cooling system helped to stably provide the required cooling capacity at high-load conditions. The mean bias error and the normalized root-mean squared error of the predicted cooling load of the building were −8% and 12.4%, respectively. The hybrid cooling system was simulated by varying four operating parameters: the operating schedule, chilled water temperature (T_{CW}), dry-bulb temperature (T_{DB}), and entering water temperature (T_{EW}). The T_{CW} is ascertained as being the most effective control parameter in the hybrid cooling system.

1. Introduction

Generally, chillers operate in sequence to satisfy the cooling loads of a building. Ground source heat pumps (GSHPs) are increasingly used for heating and cooling in commercial as well as residential buildings. A hybrid cooling system that combines a chiller with a GSHP can be applied in a building for improving the system performance. The performance of the chiller is affected by the heat rejection medium, compressor efficiency, and cooling load. However, for a hybrid cooling system, some additional operating parameters, such as the thermal environment under the ground and heat extraction rate, have to be considered for allowing the optimum operation of the system. It is worthwhile to estimate how the performance of a hybrid cooling system can be improved by optimizing the operating schedule at various load conditions. In addition, it is advisable to determine optimal strategies for energy saving in buildings by using a simulation program.

Various experimental and analytical studies have been undertaken on GSHP systems. Hepbasli [1] conducted the thermodynamic analysis of a GSHP system for district heating in terms of both energy and exergy analysis, which aimed at improving the process efficiency. Ozgener and Hepbasli [2] assessed the performance of two GSHP systems along with their essential system components, such as the compressor, condenser, evaporator, expansion valve, and pump, through a comprehensive energy and exergy analysis. Zhang et al. [3] numerically investigated the ground temperature restoration characteristics of ground heat exchangers in a large-scale GSHP system. Sankaranarayanan [4] simulated a hybrid ground source heat pump system in which supplemental heat rejecters were used together with the ground loop by using EnergyPlus.

Salsbury and Diamond [5] validated the performance of a heating, ventilation, and air conditioning (HVAC) system using a simulation model. Song et al. [6] simulated the indoor air movement and contaminant concentration in a multi-room model by using the ESP-r program. Zhou et al. [7,8] simulated a variable refrigerant flow (VRF) air-conditioning system for cooling and then compared the energy consumption of the VRF system with those of two conventional air-conditioning systems by using EnergyPlus [9,10]. They reported that the VRF system could have large potential for energy saving at part-load conditions. Yu and Chan [11] noted that the efficiency of a reciprocating chiller could be improved by more than 40%, depending on the load condition and outdoor temperature. Yu and Chan [12,13] also studied the optimal sharing strategy of loads in a combined system with two chillers by using the TRNSYS program. Oh et al. [14] investigated the optimal operation mode of a combined system with a cogeneration system by applying a mixed-integer programming approach.

Until now, many researchers have tried to develop simulation models for a combined system with multiple chillers. However, the modeling and performance evaluation of hybrid cooling systems that combine conventional chillers with GSHPs is very limited in

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Nomenclature

COP	coefficient of performance
C_p	specific heat in constant pressure, kJ kg^{-1} K^{-1}
C_v (RMSE)	coefficient of variation of the root-mean squared error, %
EIR	energy input ratio (inverse of COP)
GSHP	ground source heat pump
GHE	ground heat exchanger
$\dot{m}$	mass flow rate, kg s^{-1}
MBE	mean bias error, %
Q	refrigeration capacity, kW
SWC	screw water chiller
T	temperature, °C
$\dot{V}$	volumetric flow rate, m^3 s^{-1}
W	power consumption, kW

Greek symbols

α, β, χ	coefficients for Eqs. (8)–(10)
ε, ϕ	coefficients for Eqs. (11)–(12)
Φ	correction factor for the cooling capacity of the SWC
Λ	on–off cycling ratio of the SWC
Π	correction factor for EIR of the SWC
Ψ	correction factor for the part-load fraction of the SWC

Subscripts

AHU	air handling unit
avail	adjusted available chiller capacity
c	cooling mode
cap	capacity
CW	chilled water
cool	cooling load
DB	dry bulb
EW	entering water
in	inlet
L	load side
out	outlet
ref	reference condition
S	source side

the open literature. In this study, the performance of a hybrid cooling system that combines a screw water chiller (SWC) with a GSHP was simulated by using EnergyPlus [9] with the consideration of the system performance at partial-load conditions. In addition, the performance of the hybrid cooling system was measured in a building located in Jeju, Korea, and then compared with the predictions of the present model. Furthermore, the performance characteristics of the hybrid cooling system were analyzed according to the operating parameters by using the present simulation model.

2. Experimental setup and data acquisition

A building, which had a total area of 484 m^2, was monitored from July 2007 through October 2007 for measuring the operating data of the hybrid cooling system. Fig. 1 shows a schematic diagram of the HVAC system in the building. A hybrid cooling system that combined an air-cooled SWC with a GSHP was used in the building and two chillers were connected to a single water tank. An air handling unit (AHU) was used to supply the conditioned air to rooms in the building. The SWC and GSHP using R-22 had nominal cooling capacities of 105 kW (358,200 Btu/h) and 34 kW (115,920 Btu/h), respectively. Table 1 shows the specifications of the SWC and GSHP used in the experiment. The vertical ground heat exchanger (GHE) of the GSHP consisted of four bored holes with a nominal pipe diameter of 3.175 cm, a depth of 150 m, a single U-tube configuration, and a having distance of 4 m between each loop.

At intervals of 30 s, the following parameters were monitored and then averaged each hour: the power consumptions of the GSHP and SWC; the supply and return chilled water temperatures (T_{CW}) of both facilities; the inlet and outlet water temperatures of the cooling water for the GSHP; and mass flow rate of each working fluid. The power consumptions of the chiller (W_{SWC}) and GSHP (W_{GSHP}), which represent the total power consumption of the compressor, fan, and pump, were monitored by power meters with an uncertainty of ±0.5% in the readings. The flow rate of chilled water was measured by a turbine flow meter with an uncertainty of

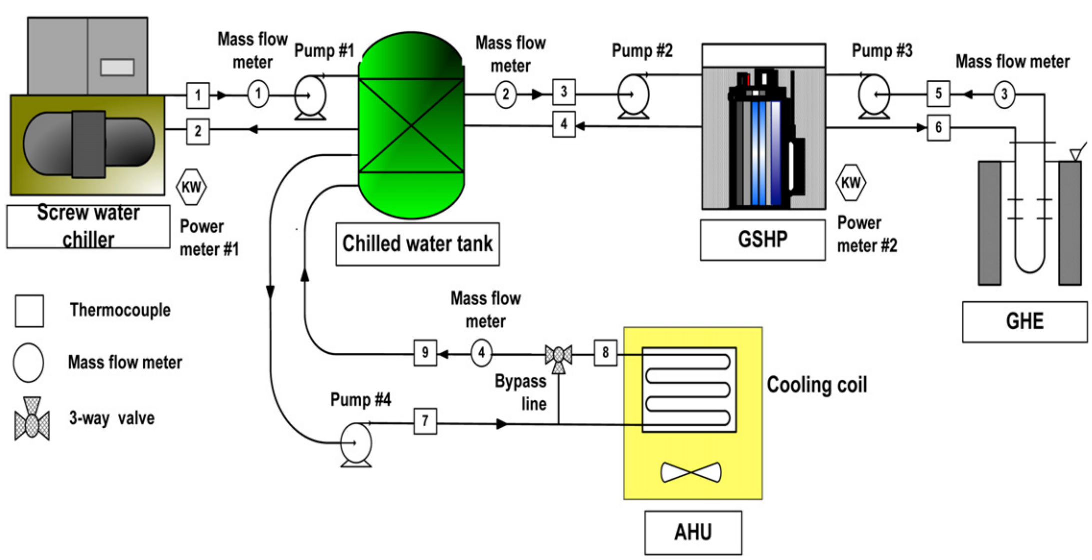

Fig. 1. Schematic diagram of the HVAC system of the building.