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Performance investigation of heat pump–gas fired water heater hybrid system and its economic feasibility study

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ABSTRACT

Heat pump water heaters have been introduced to improve energy efficiency of water heating in buildings. Although much research has been conducted to make up for weak points of heat pumps which occur when their purpose is converted from air-conditioning into water heating, there remain some points to be improved to perform as stably as conventional water heaters. Recently, the hybrid water heating system, which is the combination of a heat pump and a traditional gas fired water heater, is proposed as an alternative water heater to perform more efficient water heating stably. In this paper, the hybrid system is designed for general residential houses in Korea, which have floor area of 106.47 m^2 and its performance characteristics are analyzed numerically. To obtain the performance of a hybrid water heating system, the mathematical models of heat pump components and the correlation, which is derived from experimental data of a gas fired water heater, are applied. Also, using the result of a performance calculation, the economic feasibility study is carried out, with the concept of energy cost savings, to quantify the merits of the system and to establish its operation strategy. The monthly electricity and heat consumption data in a Korean residential house and the price of electricity and gas are applied to reflect an actual situation.

1. Introduction

Water heating is one of the largest energy usages in residential buildings, along with space heating, air conditioning, and lighting [1]. Furthermore, if the floor heating system, which has higher energy efficiency potential [2], is applied to houses, water heating becomes a dominant factor in household energy consumption because space heating is also performed by hot water. Nowadays, since more concerns about building energy saving have been raised, the energy efficiency of water heaters comes into the picture [3].

Heat pump water heating systems have been introduced as a new type of water heaters. It can supply hot water with much greater efficiency than conventional water heaters which generate heat by consuming fossil fuels or electricity [4]. However, since the desired temperature of hot water which heat pump water heaters should provide is higher than that of general heat pumps for air-conditioning, the disadvantages of air-source heat pumps at very low ambient temperature become too worse to operate effectively [5,6]. Thus, much research has been conducted to investigate and overcome those weaknesses.

Li et al. [7] analyzed a direct-expansion solar-assisted heat pump water heater which uses a bare flat-plate solar collector as an evaporator of heat pumps. They showed the performance of the system through experiments and suggested some methods to improve the efficiency of the system, especially for a collector/evaporator. Fernandez et al. [8] performed heating tests with a CO_2 heat pump water heater, which is relatively free from the restriction of high temperature and pressure because it operates as a transcritical cycle. They also investigated two alternative systems, which apply an internal heat exchanger and a suction line heat exchanger, to enhance coefficient of performance (COP) of the CO_2 heat pump water heater. Park et al. [9] proposed a cascade refrigeration system for a heat pump water heater. They conducted experiments using an R134a-R410A cascade system and found optimal intermediate temperature which enables the system to operate with its maximum COP. Long and Zhu [10] designed the thermal storage heat pump water heater of which condenser releases heat to phase change materials (PCM). They used paraffin as PCM and confirmed that the system can take advantage of off-peak electrical energy. Chen et al. [11] applied a regenerator to a heat pump water heater to recover waste heat from shower water. They developed

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Nomenclature

Bo	boiling number
COP	coefficient of performance
D	diameter of expansion valve (m)
D_c	fin collar outside diameter of tube (m)
EC	energy (electricity + natural gas) cost ($)
F_p	fin pitch (m)
g	gravitational acceleration (m/s^2)
h	enthalpy (J/kg)
*J*1, . . ., *J*4	correlation parameters
k	thermal conductivity (W/(m K))
L	length (plate, orifice) (m)
L_h	louver height (m)
L_p	major louver pitch (m)
M	molecular weight
$\dot{m}$	mass flow rate (kg/h)
p	pressure (kPa)
P_l	longitudinal tube pitch (m)
Pr	Prandtl number
P_t	transverse tube pitch (m)
Q	heat capacity (kW)
q	heat flux (W/m^2)
QR	load ratio of a gas fired water heater in hybrid system
Re	Reynolds number
rps	compressor speed (rev/s)
T	temperature (°C)
W	work (W), power consumption (kW)
x	quality
X_{tt}	Martinelli parameter

Greek symbols

η	efficiency
μ	viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

amb	ambient
e, *evap*	evaporating process
c, *cond*	condensing process, critical point
des	desired
G	gas
GWH	gas fired water heater
HP	heat pump
hyb	hybrid system
L	liquid
w	water
in	state of inlet

both static and dynamic thermodynamic models of the system and concluded that it has a large potential to reduce domestic energy consumption.

Even though many researchers have investigated a heat pump water heater with various techniques to overcome its disadvantages, there still are too many influencing factors to meet the whole hot water demand in buildings stably. Furthermore, at a time when the peak electricity demand has become a major global issue [12], it is probably not the best choice to use an electric heat pump for water heating instead of a conventional gas fired water heater despite of its high efficiency. In this situation, the hybrid water heating system, which is the combination of a heat pump and a traditional gas fired water heater, is proposed as an alternative water heater, recently. In contrast with some heat pump water heaters which use assistant electric water heaters, a gas fired water heater in this system operates at the same capacity level as a heat pump water heater. Since, this hybrid system is able to supplement the weaknesses of heat pump water heaters, which were mentioned earlier, and utilize existing equipment, many HVAC manufacturing companies, such as Daikin [13], REMKO [14], Buderus [15], etc., have been tried to launch this kind of product. However, only a little work has been conducted objectively on the hybrid water heating system, especially in open literature, even though this hybrid system has evident advantages in water heating operation.

Lately, Li et al. [16] and Klein et al. [17] modeled and investigated the hybrid system to confirm its strengths and find out the optimal operation strategy. Although they succeeded in quantifying benefits of the system and verifying the existence of optimal operation, their model for the system was a little limited to performance map and simple correlation from manufacturer. Therefore, in this study, the hybrid system is newly designed for the performance investigation, which can perform space heating combined with domestic hot water heating. The performance of the hybrid water heating system is investigated with some general mathematical models of heat pump components and the correlation which is derived from experimental data of a gas fired water heater. Also, using the result of performance calculation, the economic feasibility study is conducted to find out whether this system is economically beneficial or not. For this study, the data of heat and electricity consumption in Korean apartment houses is applied with their listed price. Finally, the operation strategy of the hybrid system, which maximizes energy cost savings, is suggested.

2. System description

The schematic diagram of a heat pump–gas fired water heater hybrid system is illustrated in Fig. 1. The hybrid system is composed of major components of a heat pump and a gas fired water heater, such as a compressor, a condenser, an expansion valve, an evaporator, and combustion chamber. Even though both a heat pump part and a gas heater part share the water line in the system, they can operate together or independently. When they work concurrently, cold water flows into a condenser first since the heat pump can operates more efficiently with low inlet temperature of water. And then, water, whose temperature is increased by a heat pump, enters a gas fired water heater and exchanges heat with hot combustion gas in a gas–water heat exchanger.

The whole system is designed for the average house in Korea which has a floor area of about 106.5 m^2. In order to meet cooling and heating loads in the building, the rated capacity of a heat pump and a gas fired water heater in the system is geared toward 23 kW and 7 kW, which is similar to that of commercial products. The capacity of heat pump is based on the condition when ambient temperature, water inlet temperature, and compressor speed are 7 °C, 30 °C, and 60 rps, respectively. The heat pump part uses R410A as a refrigerant and an inverter driven compressor to adjust its capacity. The gas fired water heater part uses natural gas as a fuel and its mass flow rate varies from 15 L/min to 30 L/min by a control valve to operate at partial load condition. The compressor speed of a heat pump and the mass flow rate of natural gas are adjusted complementarily to meet the capacity condition. More detailed specification of the system is arranged in Table 1.