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Performance analysis of a multi-functional Heat pump system in heating mode

Xiaoyu Liu [a], Long Ni [b], Siu-Kit Lau [a,*], Haorong Li [a]

[a] The Charles W. Durham School of Architectural Engineering and Construction, University of Nebraska-Lincoln, 1110 S. 67th St., Omaha, NE 68182-0816, USA
[b] Department of Building Thermal Engineering, Harbin Institute of Technology, Harbin 150090, China

HIGHLIGHTS

► Performance of a multi-functional heat pump system was investigated in heating mode.
► Better performance than conventional air source heat pump system.
► Parallel heat sources can provide better system performance.
► Supplying hot water has limited affection on heating capacity in space heating.
► Supplying hot water can improve the COP of the multi-functional heat pump system.

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ABSTRACT

A multi-functional heat-pump system is proposed to efficiently utilize the gray water as heat source and sink for heating and cooling of residential buildings, respectively. Heat is reclaimed from the plate heat exchanger installed at the outlet of the compressor to provide sufficient hot water for residential use. To study the performance of this innovative system, laboratory testing is performed with a prototype consisting of an outdoor heat pump, an indoor air handler, a gray water tank and a hot water tank. This system is set in two environmental chambers that they represent: the outdoor and indoor environments, respectively. In this paper, the investigation of the system is mainly focused on the heating performance. The system is designed to allow four combinations of two heat sources that they are a water-source evaporator and an air-source evaporator. The four combinations consist of air source only, water source only, air source and water source in parallel and air source and water source in series, in the refrigerant cycle. Performance of the four combinations of heat sources is experimentally investigated at a typical indoor air temperature of 21.1 °C and various outdoor air temperatures at 1.1, 8.3, and 15.6 °C. The results show that the heat source combinations influence the heating capacity and coefficient of performance (COP) of the system. Also, the system performance and the optimal heat source combination depend on the outdoor temperature. As outdoor temperature decreases, the variation of system performance among different combinations becomes small. The system performance in modes of space heating and space heating plus hot water supply are compared and analyzed. The COP of the system in the space heating plus hot water supply mode increases in all heat source combinations, compared with that in space heating only mode. The performance of the system for heating hot water from 30 °C to 48.9 °C is also studied. This proposed system can provide significant energy savings in space heating and hot water supply. The optimal source combination is critical in pursuing the maximum energy savings.

1. Introduction

To reduce energy consumption from buildings, U.S. Department of Energy (DOE) set a goal to achieve Zero-Net Energy Buildings from two perspectives: (i) to reduce the average energy use of housing by 40%–100% through improving building energy systems efficiency and conservation, and (ii) to offset the rest of the energy usage through on-site renewable energy generation [7]. Although it is a long way to achieve the goal, it is generally realized that the largest hurdle for renewable energy solutions is how to shorten the payback period and make them cost-effective. A lot of innovative technologies in this regard have resulted, and a lot of research is ongoing.

* Corresponding author. Tel.: +1 402 554 3861; fax: +1 402 554 2080.
E-mail address: slau3@unl.edu (S.-K. Lau).

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The oil crisis in the beginning of the 1970s has led researchers to seeking alternative energy sources [17]. Later, heat pumps became popular for heating and cooling applications. Ground source, air source, combining solar energy and geothermal heat pump were proposed by many researchers [26].

Water heating accounts for an average 18% of all residential energy use in the United States, which makes it to be the second largest use of energy in residential buildings [8]. In some states (e.g., California), this percentage of energy use can reach as high as 25%. Since the 1950s, research has been performed on heat pump water heaters [11] for energy saving. The potential energy sources (for instance, air and water sources) have been considered. Ito and Miura [14] have investigated the mechanism of heat pumps for hot water supply using combined air and water sources. The system can switch to either one or both heat sources. Direct-expansion solar-assisted heat-pump system that combined solar and air heat sources was studied in generation of hot water [5,6,9,12,18,20]. Arif [3] studies on the exegetic modeling and performance evaluation of solar-assisted domestic hot water tank integrated geothermal heat pump systems for residences. However, this research work mainly focuses on saving energy in supplying hot water, and did not consider the possibility of saving energy for integrating air conditioning and hot water supply systems.

Water heating is just a part of total energy consumption. In fact, the space heating and cooling consume a significant portion of energy consumption. Heat-pump water-heaters are designed for service water heating and their hot water production rate are only 40–100% of that of the electric heating devices and 30–50% of that of the gas heating devices [15]. To provide quick recovery with this type of water heater, a household must have a large heat pump, an unusually large storage tank, and an electric backup heater. However, this electric backup heater will increase peak electrical demand and reduces energy efficiency [15].

To further improve the application area of heat pumps and energy utilization, numerous researchers are focusing on investigation of multi-functional heat pump system that not only provides hot water but also space heating and cooling. In residential buildings, the load of hot water can be satisfied by the multi-functional heat pump systems, meanwhile space cooling and heating can be provided. Ni et al. [21] investigated this type of system numerically, and showed the mean of daily hot water load in a typical residential house in New York is about 33.6 MJ. The study is based on a calculation using the methods provided by Building America Research Benchmark [27]. Considering the hourly usage profile [25,27], the mean hourly load of hot water is about 1400 kJ. Through numerical simulation, Ni et al. [21] concluded that the total source energy savings have a range of 17%–57.9% among 15 cities in different climate zones in the U.S. Hot water heating has the most significant energy savings with over 60% reduction. Ji et al. [15,16] developed a prototype system and simulation program for an integrated domestic air-conditioner and water heater. Kara et al. [17] and Kuang and Wang [19] applied the direct expansion solar-assisted heat pump for space heating, space cooling and hot water supply. Ozgener and Hepbasli [22–24] developed a multi-function heat pump system by utilizing solar energy and geothermal heat.

Waste water discharge by the residential building is also an important heat source. Baek et al. [4] have carried out a numerical study of a heat pump system using waste water. The system showed comparably high COP. However, the results were acquired from numerical simulation and this system is only for heating low-temperature hot spring water. The performance of a system supplying space heating, space cooling and hot water simultaneously using waste water was not investigated. Compared with the solar assisted heat pump system or geothermal system, air source and waste water source heat pump system are comparably economical, especially in initial cost. In addition, the geothermal heat pump has a regional limitation. However, waste water source and air source do not have the similar limitation.

This paper proposes a prototype multi-function heat pump system with utilizing air and waste-water heat sources. Ni et al. [21] have given a feasibility study of this heat pump system. The system operation strategy and energy savings has been numerically analyzed. An author of this paper has been involved in the development a gray water treating system consisted of a simple screen, a bio-filter filled with shredded tire chips and a membrane bioreactor for this application [13]. The Heat pump system has been built by a modification of conventional air source heat pump. Therefore, retrofit of existing heat pump system is possible and can reduce the initial investment and improve the energy utilization efficiency.

There are four types of combinations with air source and waste water source, consisting of “air source only”, “water source only”, “air and water sources in parallel” and “air and water in series”. The “air source only” uses the outdoor air heat exchanger alone, while the “water source only” uses the heat exchanger, located in the gray water tank. The “air and water sources in parallel” represents the heat exchangers, located in the outdoor chamber and the gray water tank, are configured in parallel. The “air and water sources in series” represents the heat exchangers, located in the outdoor chamber and in the gray water tank, are configured in series. In the present study, the system performance in different functions with different types of heat source combinations will be discussed.

2. Prototype setup

To study the performance of the multi-functional heat pump system, a prototype system is setup at a laboratory in the University of Nebraska-Lincoln, which consists of a heat pump system and a hot water supply system. The system is installed in two separate laboratory rooms that represent outdoor and indoor environments, respectively. The heat pump system consists of a compressor, an accumulator, a heat exchanger with a fan in the outdoor chamber, an indoor air handler including a heat exchanger and a fan, and a gray water tank with an immersed heat exchanger, as shown in Fig. 1(a). The immersed heat exchanger in the gray water tank is DX (Direct Expansion) coil. DX coil is easy to maintain and clean than shell and tube heat exchanger, although it has lower heat transfer efficiency. The hot water supply system consists of a water pump for circulating water in the pipe, a 30-gallon hot water tank for storage of hot water, and a plate heat exchanger for heating hot water.

In this prototype system, one four-way valve is installed at the outlet of the compressor to switch between heating mode and cooling mode. As shown in Fig. 1(a), six solenoid valves are used to guide the refrigerant bypassing different heat exchangers. There are two throttling valves being used for heating mode and cooling mode, which are a thermal expansion valve and a metering device, respectively. The pressure and temperature of refrigerant flow is measured at the locations as shown in Fig. 1(a). Six pressure sensors are installed at different positions to measure the pressure distributions of the refrigerant flow. Temperatures are measured with copper–constantan thermocouples and platinum resistance thermometers. The air flow rate and temperature of the air source heat exchanger are also measured. An in-line water flow meter is used to measure the hot water flow rate. A digital power meter is used to measure the overall power consumptions of the compressor and the fans. All of the above measuring processes are monitored and controlled by a National Instruments data acquisition system. The data is recorded at each 1 s interval. The range and accuracy of the sensors installed in the system are shown in Table 1.