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Performance analysis of a multi-functional heat pump system in cooling mode

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HIGHLIGHTS

- Performance of a multi-functional heat pump system was investigated in cooling mode.
- Better performance than conventional air-source heat pump system.
- Series heat sink combination can provide better system performance.
- Gray water temperature has limited impact on parallel and series.
- Supplying hot water can improve the *COP* and cooling capacity for space cooling.

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ABSTRACT

A multi-functional heat pump system is proposed to effectively utilize waste heat and heat capacity in gray water for heating or cooling of residential buildings. Heat is also reclaimed from a plate heat exchanger installed at the discharge outlet of the compressor to provide sufficient hot water for residential use. To study the performance of this innovative system, laboratory testing has been 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 mimic the outdoor and indoor environments, respectively. In this paper, the investigation of the proposed system is focused on the performance in cooling mode. The multi-functional heat pump system has been run under (i) space cooling mode and (ii) space cooling plus hot-water supply mode, with the same temperature conditions. The system performances in these two modes are compared and analyzed. The system is designed to allow four combinations of heat sinks with a water sink condenser and an air sink condenser. The four combinations are (1) air sink only, (2) water sink only, (3) air sink and water sink in parallel and (4) air sink and water sink in series, at the refrigerant cycle. Performance of the four combinations of heat sinks is experimentally investigated at a typical indoor air temperature of 26.7 °C and various outdoor air temperatures at 29.4 °C, 35 °C, and 40.5 °C. The results show that the heat sink combinations influence the cooling capacity and coefficient of performance (*COP*) of the system. The system performance and the optimal heat sink combination depend on the outdoor temperature. The impacts of outdoor temperature and gray water temperature on the performance of the system are discussed. The dynamic performance of the system for heating hot water from 30 °C to 48.9 °C is also studied. The proposed system has been shown providing significant energy savings in space cooling and hot-water supply. Moreover, the optimal source combination is critical in pursuing the maximum energy savings.

1. Introduction

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 [1]. In some states (e.g., California), the portion of energy use can reach as high as 25% of the total energy consumption. In a conventional building system, water heating usually is done by electricity or gas unit. However, this method consumes much energy compared with using heat pump systems. Therefore, heat pumps are becoming more popular for heating and cooling applications in residential buildings for energy saving. Ground-source and air-source heat pumps, as well

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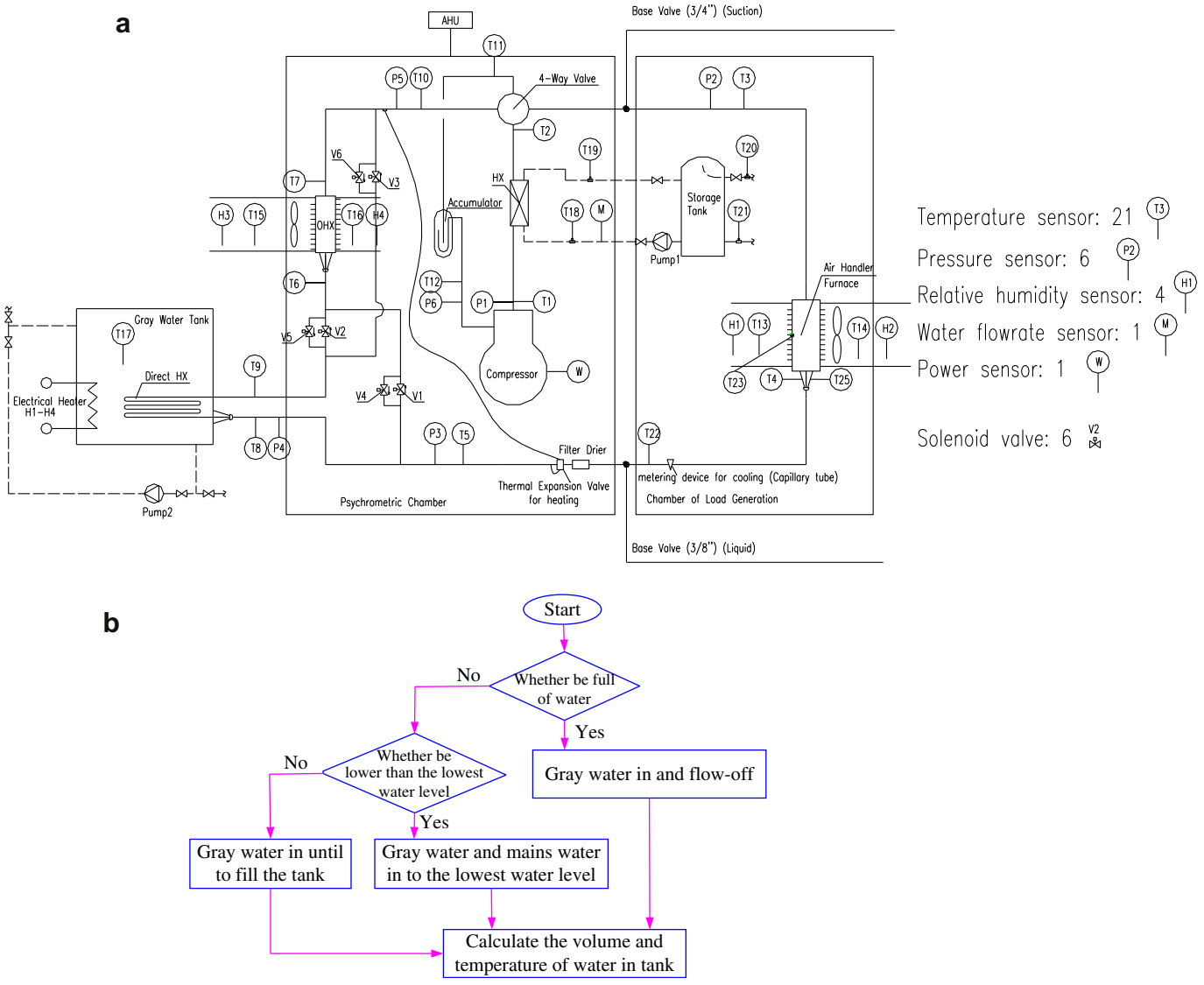

Fig. 1. (a) Schematic diagram of the prototype (multi-functional heat pump system). (b) The operation strategies of gray water tank.

as combining solar energy and geothermal heat pump, were proposed by many researchers [2]. Since the 1950s, research has been performed on heat pump water heaters [3] for energy saving. The potential energy sources (for instance, air and water) have been considered. Ito and Miura [4] have investigated the mechanisms 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 has been proposed to generate hot water [5–10]. Arif et al. [11,12] have been investigated exegetic modeling and performance evaluation of a solar-assisted domestic hot-water tank integrated geothermal heat pump systems for residential buildings has been performed. However, their research works are focused on saving energy in supplying hot water, and did not consider the potential energy saving with integration of air conditioning and hot-water supply systems. Heat pump water heaters for service water heating have hot-water production rate only 40–100% of that of the electric heating devices and 30–50% of that of the gas heating devices [13]. 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 overall energy efficiency [13].

Water heating is just a part of total energy consumption in buildings. In fact, the space heating and cooling consume a significant amount of energy. To further improve the energy efficiency of heat pumps in various applications, numerous researchers have investigated 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. [14] investigated this type of system numerically, and showed the mean of daily hot-water load at 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 [15]. Considering the usage profile [15,16], the mean hourly load of hot water is about 1.4 MJ. Through the numerical simulation, Ni et al. [14] 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. using a combined heat pump system for hot-water heating and space heating and cooling. Reclamation of heat from the gray water was considered in their