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Optimization and analysis of a multi-functional heat pump system with air source and gray water source in heating mode

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ABSTRACT

A multi-functional heat-pump system utilizing the ambient air and gray water as heat source and sink has been optimized for heating and cooling of residential buildings, respectively. This optimization is made based on an existing prototype of the multi-functional heat pump system in the authors' previous study [1,2]. The optimized prototype consists of a heat pump system and a hot water supply system. The prototype is set in two environmental chambers that they simulate the outdoor and indoor environments, respectively, for performance testing. The system was designed to allow four combinations of a water-source evaporator and an air-source evaporator acted as heat sources in space and/or hot water heating modes. The four combinations consist of (a) air-source-only, (b) water-source-only, (c) air-and-water-sources-in-parallel, and (d) air-and-water-sources-in-series, in the refrigerant cycle. In this paper, the drawbacks of the initial prototype in heating mode are discussed and the modifications are proposed. The results show that the performance of optimized prototype superior to that of initial one. The optimized multi-functional heat pump system, compared with initial prototype, can be more practical and provide significant energy savings in space heating and hot water supply.

1. Introduction

Heat pumps are popular for heating and cooling applications. Ground source, air source, combining solar energy and geothermal heat pump were proposed by numerous researchers [3]. Ambient air is an excellent source in terms of availability, thus air source heat pumps are widely used and comparably low initial cost. Compared with other heat sources, air source generally has two problems: (1) the absolute temperature level compared with most other heat sources is relatively low and (2) the annual temperature variation makes the heat output characteristics for the heat pump become quite opposite to the desired one, i.e. low capacity when it is cold outside [2]. Solar source is green and free energy source. Kara et al. [4] and Kuang and Wang [5] applied the direct expansion solar-assisted heat pump for space heating, space cooling and hot water supply. Solar energy has the advantage of not increasing the heat load for the earth and also be safe for the environment and ecological [6]. Ground source can provide vast geothermal energy that is also green and free. Ozgener and Hepbasli [7–9] developed a multi-function heat pump system by utilizing solar energy and geothermal heat. The major disadvantage of solar source and ground source heat pumps is the high initial cost. Moreover, the heat balance of soil may be a problem for maintaining high operational efficiency of the ground source heat pump. Gray water, that is a type of wastewater, is discharged from buildings which usually have a higher temperature than that of outdoor air and freezing. Wastewater source comes from cold and hot water usages in buildings, and thus it is an intermittent source. Numerous researchers have investigated the utilization of multiple heat sources to overcome some abovementioned weakness of a single heat source and to improve the heat pump system performance. Parallel and serial configurations are two fundamental configurations of the heat exchangers for heat pumps with multiple heat sources. Ito and Miura [10] study the parallel combinations of air source and water source via experiments. They find that the system with dual heat sources may have a higher evaporation temperature and COP than the case of a single heat source. Liu and Bullard [11] developed simulation models of a heat pump with multi evaporators. However, there is a lack of publications found by the authors on the series configuration of heat exchangers using different heat sources.

In the U.S. residential buildings, the largest energy consumption is space heating, followed by the water heating and the space cooling, as shown in Fig. 1. The space heating accounts for about 45%, which is almost half of the total energy consumption in residential buildings. Water heating consumes 18% of the total energy

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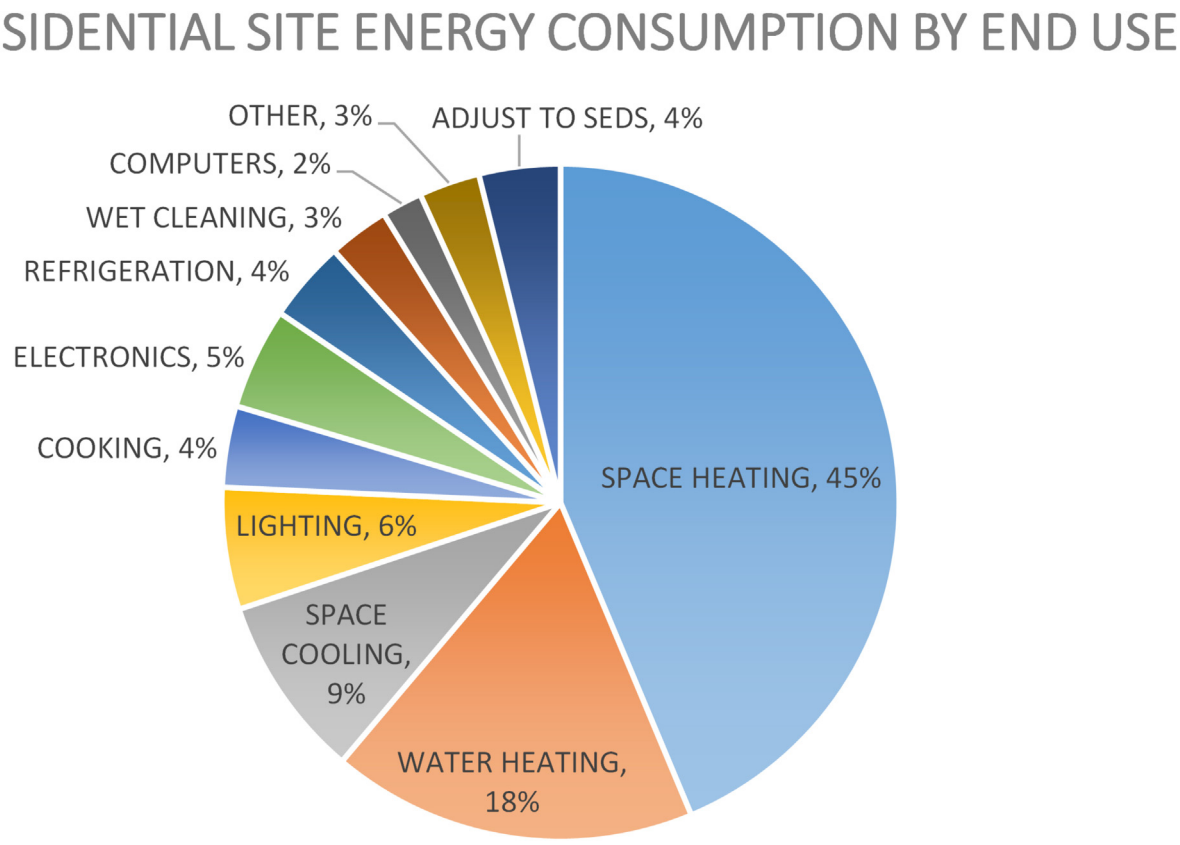

Fig. 1. Residential site energy consumption in the U.S. by end-use [39].

consumption and the percentage of energy consumption for space cooling is half of that for water heating in residential building. Obviously, space heating, water heating and space cooling play essential roles on energy savings. The potential energy sources (for instance, air and water sources) have been investigated [10,12–18]. These research works have been focused on saving energy in supplying hot water, and did not consider the possibility of saving energy using integrating air conditioning and hot water supply systems. Heat pump water heaters have disadvantages of comparably low hot water production rate, large storage tank and the requirement of extra electric backup heater [19].

Ying [20], Cook [21], Goldschmidt [22] and Toh and Chan [23] investigated on recovery of condenser heat from the air conditioner to supply hot water while providing space cooling. From their experimental and numerical results, they observed that the COP of the system could be increased while supplying domestic hot water do not lower down the cooling capacity. Jiang et al. [24] further investigated the recovery of condenser heat in air conditioners via experiments. Substantial energy savings was confirmed by their works. It is noted that air conditioners are only operating at some periods of time over the year in winter and summer; however, the daily demand of hot water is almost stationary throughout all year around. Therefore, a major limitation for the auxiliary condenser heat recovery system is that hot water is not always available. It is because condensing waste heat is only available while air conditioners operate in cooling mode [24]. Moreover, this kind of heat recovery only can reclaim approximately 10–25% condensing heat in total condense heat [25].

To improve the performance of heat pumps, previous studies have investigated the multi-functional heat pump system that not only provides hot water but also space heating and cooling. The research work can be divided into groups with simulations and experiments, respectively. Techarungpaisan et al. [26] built the steady-state model of a split type air conditioner with integrated water heater. Murphy [27] developed the multi-functional air source heat pump system which can provide space heating, space cooling and hot water based on TRNSYS platform. Rad et al. [28] developed a multi-functional heat pump system model that utilizes solar source and ground source. In their study, the energy savings of the system applied in six cities in Canada are presented. Ji et al. [19,29] has developed a prototype system and simulation program for an integrated domestic air-conditioner and water heater. Hong [30] built a prototype of multi-functional solar assisted air source heat pump system. These research works mainly focus on the residential buildings application. Coskun et al. [31] proposed and studied the application in industrial of a novel hybrid district energy system utilizing geothermal and biogas. However, a multi-functional heat pump system utilizing the heat from gray water and with different heat source combinations is not investigated in previous research.

This paper proposes an optimized prototype of a multi-function heat pump system with utilizing air and gray-water heat sources focusing on improving the overall efficiency of the energy utilization in residential buildings. Liu et al. [1,2] has experimentally studied the performance of an initial prototype of the multi-functional heat pump system. An author of this paper has been involved in the development of 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 [32]. Through optimization of the initial prototype, current prototype shows better performance and stability in use. In the present study, the system performance in different functions with different types of heat source combinations in heating mode will be discussed.