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Experimental performance analysis of an improved multifunctional heat pump system

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ABSTRACT

An improved multifunctional heat pump (MFHP) system that integrates an air-source evaporator and a water–water heat exchanger was developed. An experimental set-up and a mathematical model were constructed to evaluate the performance of the MFHP system. Some characteristics of the system, such as the effects of water–water heat exchanger, hot water outlet temperature, and cooling capacities of the air-source and water-source evaporators, were discussed based on experimental data. Experimental results show that the MFHP system could simultaneously supply hot water for bathing and cold air for air conditioning. In addition, the coefficient of heating performance (COP_h) varied from 3.69 to 5.70. Analysis results show that the COP_h and the hot water volumetric flow rate of the MFHP system were closely related to the inlet and outlet temperature of hot water and wastewater. Empirical models of COP_h and hot-water flow rate were proposed to predict the heating performance of the MFHP system. The improved MFHP system is shown to have satisfactory energy saving performance.

1. Introduction

Hot water is generally produced by various types of water heaters, such as gas, solar, and heat pump water heaters, to supply artificial springs, sauna rooms, and domestic and commercial facilities. However, the waste hot water generated from bath/shower is directly drained into the environment, thus resulting in thermal pollution and energy waste. Our experimental results show that the temperature of hot waste shower water is above 30 °C in hot climate areas such as Shenzhen, a city in Southern China. This hot waste shower/bath water is suitable as a heat source of heat pump water heaters in those areas. On the basis of the research published by Chen and Li [1], Ji et al. [2], and others [3–6], Wang developed a small-scale shower wastewater source heat pump (SWWHP) that utilizes bath/shower wastewater as heat source to save energy in hot climate areas [7]. An improved multifunctional heat pump (MFHP) system with an efficient redesigned air-source evaporator and an enhanced water–water heat exchanger was proposed based on the original SWWHP. The MFHP system can produce enough hot water for bathing, heating, or air conditioning by recovering heat from hot wastewater and air.

Many researchers have studied the models of heat pump water heaters to predict the system performance of this technology. For instance, Meggers et al. used heat pump supply temperature T_h, evaporator temperature T_c, and the temperature-lift ($\Delta T = T_h - T_c$) as variables to calculate the coefficient of heating performance (COP_h) of the system [8]. They also proposed a model by using the T_h, T_c, and heat transfer characteristics of the recovery tank to evaluate the average coefficient of performance (COP_{ave}) during a given period. Kim et al. investigated a residential air-to-air heat pump system and proposed the first-, second-, third- and fourth-order multivariable polynomial regression (MPR) reference models and an artificial neural network (ANN) reference model by using outdoor dry-bulb temperature T_{OD}, indoor dry-bulb temperature T_{ID}, and indoor dew point temperature T_{IDP} as independent variables [9]. These models [9] could be used in predicting the performance of air-to-air heat pumps if enough data were available. Greyvenstein developed a computer simulation model for water-to-air heat pumps on the basis of database parameters, such as characteristics of compressor and heat exchangers [10]. A detailed database should be prepared to calculate the refrigerant flow rate and the input power of the system to meet model requirements when using the Greyvenstein model. Stefanuk et al. modeled a superheat-controlled water–water heat pump on the basis of energy, mass, and momentum conservation laws, as well as heat transfer relations. However, the model required many available characteristic parameters of the components. For instance, the compressor characteristics were determined by using the curve-fitting method under different mass flow rates of the refrigerant, input power, evaporation temperature, and compressor discharging pressure

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Nomenclature

A, B, C, D	constants in Eqs. (7) and (8)
a_1, b_1, c_1	constants in Eq. (6)
c	specific heat of water (kJ/(kg °C))
COP_h	coefficient of heating performance
F	supply-air area of air-source evaporator (m^2)
h	specific enthalpy (kJ/(kg °C))
N	input power of compressor (kW)
Q	heat capacity (kW)
T	temperature (°C)
V	volume flow rate (m^3/h)
v	velocity of air flow (m/s)

Greek symbols

ΔT	temperature difference (°C)
ρ	density (kg/m^3)

Superscripts and subscripts

A	air
AE	air source evaporator
A,in	return air of air source evaporator
A,o	supply air of air source evaporator
c	condenser
e,t	total cooling capacity of the MFHP system
hw	hot water
hw,in	inlet of hot water
hw,m	middle status of hot water
hw,o	outlet of hot water
loss	heat loss of the MFHP system
w, or ww	wastewater
WE	waste source evaporator
ww,in	inlet of wastewater
ww,m	middle status of wastewater
ww,o	outlet of wastewater

[11]. On the basis of thermodynamic principles and heat transfer relations, Jin et al. developed the water–water heat pump model, which is a parameter estimation-based model [12]. Their model also depended on many parameters and characteristics of heat pump components. They selected eight parameters, namely, the compressor clearance factor, the constant part of the electromechanical power loses, the loss factor defining the electromechanical loss proportional to the theoretical power, superheat, heat transfer coefficients of condenser and evaporator, suction pressure drop, and discharge pressure drop, to solve the compressor model.

In this paper, the authors investigated the experimental characteristics of the MFHP system and proposed novel empirical models to evaluate the performance of the MFHP system.

2. Description of the MFHP system

The schematic diagram of the improved MFHP system is shown in Fig. 1. The system comprises a compressor, a condenser, a set of capillary tubes, a water–water heat exchanger, a wastewater source evaporator, and an air-source evaporator. The MFHP system can be installed inside or outside a bathroom. This improved system can supply hot water in a short time (e.g., 13 s in summer) after the heater is turned on. Compared with conventional air-source heat pump water heaters, the MFHP system is more compact and more convenient to use because the MFHP system does not require a hot water tank to operate. Hot water tanks are also necessary for many water–water heat pump systems, such as [8,13]. Furthermore, the improved MFHP system does not require any valve in the refrigerant loop, which makes this system distinct from the research of Lazzarin [14]. Lazzarin [14] investigated two types of dual-source heat pumps. One heat pump had two evaporators that could be arranged in series or in parallel, namely, an air-source evaporator and a water-source evaporator that uses solar-heated water. Their system [14] was flexible but required change-over valves in the refrigerant pipes to connect the air-source and water-source evaporators. By contrast, the MFHP system can effectively reduce cost and avoid refrigerant leakage because the system does not contain valves in the refrigerant loop. The MFHP system can operate in two modes:

(1) Water heater mode: hot water is supplied solely by turning off the fan of the air-source evaporator;
(2) Water heater and air-conditioning mode: hot water and cold air are supplied simultaneously. In this mode, if necessary, the water-source evaporator can operate or not. The wastewater in the water-source evaporator should be drained if the water-source evaporator is not operating. Thus, the MFHP system recovers heat from air to supply hot water.

Mode 2 is the key mode of the MFHP system. Therefore, only the experimental results of mode 2 will be introduced and analyzed in this work.

The operating process in mode 2 can be simplified in the following steps.

First, the gas refrigerant is compressed by the compressor and then enters into the condenser. The refrigerant vapor then condenses and releases heat to the city water, which is preheated by a water–water heat exchanger. The temperature of the city water reaches above 40 °C by absorbing heat from the refrigerant in the condenser. The condensed liquid refrigerant flows through a heat exchanger (HEX in Fig. 1) to be sub-cooled and then enters into the air-source evaporator after being throttled by a set of capillary tubes. The low-temperature throttled liquid refrigerant absorbs heat from the air, and part of the liquid refrigerant evaporates. Subsequently, the refrigerant enters into the water-source evaporator and evaporates completely. The refrigerant vapor generated in the water-source evaporator enters into the heat exchanger, in which heat exchange occurs between the refrigerant vapor from the water-source evaporator and the liquid refrigerant from the condenser. The refrigerant vapor is then drawn into the compressor, thereby initiating the next circulation. In the MFHP system, the air-source and water-source evaporators are arranged in series instead of in parallel to maintain different evaporating temperatures. Setting any valve in the refrigerant loop is unnecessary, which simplifies the structure and operation of the MFHP system. A split-type evaporator is used as air-source evaporator, which makes the easy installation of the MFHP in applications.

Before the MFHP initiates, city water (or tap water) should be added into the wastewater collector to ensure normal operation of the MFHP system if wastewater is unavailable. As soon as hot water is discarded from the shower, the wastewater from the shower is collected in the wastewater collector and then pumped into the water-source evaporator to release heat to the refrigerant. Some wastewater that flows from the water-source evaporator returns to the wastewater collector to supplement the amount of wastewater, thereby avoiding additional consumption of city water and preventing wastewater from having excessive low temperature. Even it will reduce the temperature of wastewater in the wastewater collector, this process is still acceptable. For example, the temperature of the mixed wastewater is relatively low (10.9 °C) during starting period. Nevertheless, the temperature gradually increases until it reaches a constant value. The recirculation of wastewater has the following advantages: