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Research paper

Research on the performance of the household-type cooling–heating–hot unit in winter

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HIGHLIGHTS

- Performance of a CHU pump system was investigated in winter mode.
- A prototype of CHU is designed and experimented.
- COP increases with the rise of outdoor temperature in air source mode.
- COP increases with the increasing water flow in water source mode.
- Performance in water source mode is better than air source mode.

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ABSTRACT

A smart air conditioning unit with functions of cooling, heating and hot water supply (referred to as CHU) is proposed for heating or cooling of residential buildings. The CHU can provide cooling and heating as regular heat pump air conditioning, and also produce hot water by recovering condensation heat in summer. To study the performance of this innovative system, a prototype machine of CHU is implemented consisting of compressor, water pump and data acquisition system. In this paper, the investigation of the proposed system is focused on the performance in winter mode. Firstly, the performance of CHU for generating hot water is tested in the air source heat pump mode. Furthermore, experiments are executed on the air source and water source heat pump modes, respectively, to test the operation performance in winter conditions. The experimental results show that the system's coefficient of heating performance (COP) decreases with the condenser inlet water temperature, which selected R22 as the refrigerant material. Besides that, both modes show significant energy saving and environmental benefits, with the COP in water source mode a little larger than in air source mode.

1. Introduction

The current energy shortage worldwide prompts people to explore ways to save energy and improve the effectiveness of energy utilization [1,2]. According to the energy efficiencies in different countries, 43–70% of energy is lost as waste heat, while a large proportion is the condensation heat in air conditioners [3]. Much attention has been paid to the reuse of condensation heat in air conditioners for domestic hot water supply since 1980s. The existing works focus on the feasibility of recycling condensation heat for small refrigeration air conditioning systems, the impact on system stability, evaluation of cost-effectiveness, and construction of simulation models.

In 1965, Healy and Wetherington first used condensation heat from air conditioners in residential building as the heat source for hot water supply, and validated their computations through experimental devices [4]. The coefficient of performance (COP) in different seasons in a heat pump system equipped with a superheated steam desuperheater was computed with the BIN method [5]. The main factors that influence the COPs in different seasons include outdoor temperature, usage mode, and the amount of hot water [5]. When the cost-effectiveness and performance of a heat pump hot water heater were evaluated using recycled waste heat for domestic hot water supply, the heat pump had great energy

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conservation potential and was economically viable [6]. Its cost-effectiveness is dependent on its design, as well as the place and way of its usage. In terms of modeling hot water unit exploited from condensation heat, a model for dynamic simulation of a heat pump hot water system was devised and the transient characteristics were studied [7]. A model of a multi-purpose domestic heat pump system was constructed with simulation and performance tests [8]. The simulation results and test results are slightly different, which validates the correctness of the model [8]. Experiments were conducted to verify the performance of a multi-functional heat pump system in heating and cooling modes, which consisted of four combinations: air source only, water source only, air source and water source in parallel, and air source and water source in series [9,10]. The results show that the system could provide significant energy saving in space heating and hot water supply.

In China, the research on the condensation heat of small refrigerating air conditioners can be traced back to 1960s, but the development is very slow [11]. In recent years, Chinese scholars put forward the condensing heat recovery of household air conditioners for domestic hot water supply, and qualified the feasibility and economy of the system, based on characterization of domestic hot water load and air-conditioning load [12–14]. They think the condensation heat of an air conditioner is enough to satisfy domestic hot water consumption [12–14]. A heat pump system, which could operate year-round by recovering the heat from air-conditioning condensers in summer, was designed by adding a preheater, a hot water pump and a water tank [12]. Apart from that, a novel air-conditioning product that can achieve the multi-functions with improved energy performance was introduced (Ji et al.). Experiment results show that the energy performance can be improved considerably. However, their further application of the proposed systems is limited by high complexity and high investment cost.

The intensified promotion of air conditioners to residential buildings in China results in rapid increase of energy consumption in the context of rising demand for domestic hot water supply [1,15]. Most of hot water heaters in the market are based on electricity, gas, solar energy and heat pump. Unlike electric heaters that are faced with electric leakage risks and continue to heat even without water, gas heaters may emit harmful gases during operation, while solar heaters cannot operate during cloudy or rainy days. In comparison, heat pump heaters completely eliminate these security risks and can work without solar energy. However, the early investment of heat pump heaters is too high, which impedes their promotion in the market [16,17].

If the heat pump system of a domestic air conditioner is organically integrated with a hot water heater, an air conditioner and a heater can work collaboratively and enable the reuse of condensation heat from the air conditioner for domestic hot water supply. It could improve the refrigeration efficiency of the air conditioner, provide a large supply of free hot water and alleviate environmental pollution. Therefore, we design a domestic three-purpose unit (i.e. cooling, heating and hot water) and make a prototype. In order to study the performance of the proposed system, we set up an experimental system in an actual house. This paper focuses on experiments into the operation of the proposed system in winter.

2. Design of the proposed prototype

2.1. Prototype description

The purpose of CHU is to achieve reasonable and efficient energy use within residential building by integrating the heating system, the air conditioning system and the domestic hot water system. It is designed to generate heat for winter, provide cool air for summer and supply hot water throughout the year.

Fig. 1 shows the schematic diagram of the proposed CHU prototype. This prototype consists of a cryogen recycling subsystem and a water recycling subsystem. The cryogen subsystem is based on a traditional vapor compression refrigeration system and also equipped with a plate-type evaporator E2. The compressor has a rated power of 2.7 kW. Furthermore, a finned tube evaporator and a double pipe condenser are adopted, with R22 as the refrigerant material. The water system consists of a domestic hot water component and a cooling/heating water component, with a tank capacity of 146 L. In addition, the water tank contains heat transfer coils and an auxiliary electric heater in case of need.

The CHU operates year-round in the following ways. To produce domestic hot water in summer (EV1 and EV3 off; EV2, EV4, pump10 and pump11 on), the heat is also derived from outdoor air if the inside supply is insufficient (EV2 and pump11 off; EV1 and pump10 on). For transitional seasons, heat is derived from air to produce domestic hot water, which then indirectly heats the indoor environment (EV2 and EV4 off; EV1, pump10 and pump11 on). In winter, the domestic hot water is supplied via warm water (EV2, EV4, pump10 and pump11 on; EV1 and EV3 off) or the heat from outdoor air (EV1, EV4 and pump10 on; EV2, EV3 and pump11 off).

2.2. Experiment principles

According to the definition of the COP of the heat pump system,

$$\mathrm{COP} = \frac{\dot{Q}_\mathrm{c}}{\dot{W}_\mathrm{C}} = 1 + \frac{\dot{Q}_\mathrm{e}}{\dot{W}_\mathrm{C}} \tag{1}$$

where $\dot{Q}_\mathrm{c} = c_\mathrm{W}\dot{m}_\mathrm{cW}(t_\mathrm{ci} - t_\mathrm{co})$, $\dot{Q}_\mathrm{e} = c_\mathrm{W}\dot{m}_\mathrm{eW}(t_\mathrm{ei} - t_\mathrm{eo})$. Then Eq. (1) could be modified as follows:

$$\mathrm{COP} = \frac{c_\mathrm{W}\rho_\mathrm{W}\dot{V}_\mathrm{cW}(t_\mathrm{ci} - t_\mathrm{co})}{\dot{W}_\mathrm{C}} \tag{2}$$

where $\dot{Q}_\mathrm{c}$ is the condenser's heat release in kW, c_W is the specific heat of water in kJ/(kg °C), $\dot{m}_\mathrm{cW}$ is the mass flow of side water in the condenser in kg/s, $\dot{m}_\mathrm{cW} = \rho_\mathrm{W}\dot{V}_\mathrm{cW}$, ρ_W is water density in kg/m^3, $\dot{V}_\mathrm{cW}$ is the volume flow rate of side water in the condenser in m^3/s, t_ci and t_co are water temperatures at the condenser's inlet and outlet in °C, $\dot{Q}_\mathrm{e}$ is the heat amount absorbed by the evaporator in kW, $\dot{m}_\mathrm{eW}$ is the mass flow of side water in the evaporator in kg/s, $\dot{m}_\mathrm{eW} = \rho_\mathrm{W}\dot{V}_\mathrm{eW}$, $\dot{V}_\mathrm{eW}$ is the volume flow rate of side water in the evaporator in m^3/s, t_ei and t_eo are the water or wind temperature at the evaporator's inlet and outlet in °C, $\dot{W}_\mathrm{C}$ is the total power of the heat pump (including compressor, water pumps and blower) in kW.

2.3. Layout of test points in the experiments

The platform for testing CHU thermal performance is designed and constructed, with consideration into CHU characteristics (Fig. 2).

Parameters that need to be measured include: t_ci, t_co, t_ei, t_eo, water temperatures at the upper and lower part of the hot water tank, temperature of air drawn or evacuated by the compressor, cryogen temperature at the evaporator's outlet, cryogen temperature at the condenser's outlet, temperature of cryogen reaching or leaving the expansion valve, flows of side water in the evaporator