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Experimental performance evaluation of a novel heat pump water heater assisted with shower drain water

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HIGHLIGHTS

- A novel heat pump water heater assisted with SDW for small single family was proposed.
- The system performances under different conditions were experimented and discussed.
- Approximately 70% of energy could be saved using this novel system compared to electrical water heater.

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ABSTRACT

Since the temperature of shower drain water (SDW) is relatively high, lots of heat is wasted with the discharge of SDW. Therefore, the recovery of this unutilized heat from SDW shows great potential in improving the building energy efficiency. In this paper, a novel heat pump water heater assisted with SDW for small single family was proposed, which could effectively recover the energy in domestic SDW. To improve its performance, a shower waste heat extraction device (WHED) with water pre-heated loops was designed. A prototype of the system was firstly set up, and then the system performances under different conditions were experimented and discussed. The experimental results showed that approximately 70% of energy could be saved using this novel heat pump water heater, compared with the traditional electric water heater. Furthermore, the COP of the system could be improved observably when using water pre-heated loops. Thus the implementation of this novel heat pump water heater was verified to be capable of reducing energy usage and CO_2 emissions significantly.

1. Introduction

According to some statistics, the energy consumption of domestic hot water per year in China reached up to 14.5 million tons standard in 2011 [1]. As a result, reducing energy consumption in domestic hot water is a key strategy to energy conservation. Among those energy-consuming devices, shower water heater is one of the most commonly used domestic electrical appliances, which accounts for approximately 20% of the residential buildings energy consumption [2].

In the past few decades, energy saving of hot water systems in buildings has been studied by a lot of researchers with respect to various components, such as solar collectors [3,4], heat pump [5–7], and heat recovery system [8,9] on the level of both technology and equipment. In Greece, the installation of solar collectors in apartment buildings can save 60–74% of energy, mainly depending on the building locations and climatic conditions. Li et al [5] carried out an experimental setup of direct expansion solar assisted heat pump water heater (SAHPWH), and analyzed the effect of ambient temperature and solar radiation on the system performance. The results showed that the system performance was significantly influenced by collector area, ambient temperature, and solar radiation. In addition, Wu et al [10] put forward a cascade air-source heat pump water heater (AHPWH) with phase change material for thermal storage application. However, the system performance was still not good enough at low ambient temperature. In particular, waste water source heat pump (WWSHP), as an energy-saving and environmentally friendly technology in the field of water heating, has been investigated both experimentally and analytically. Liu et al [11] enhanced a heat pump system assisted with solar energy used in public shower facilities for exhaust heat recovery, and this was accomplished by using a drainage collector to collect the used shower water and an electrical pump to recycle the exhaust heat. Shen et al [12–14] designed a novel dry-expansion

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Nomenclature

A_o	heat transfer area (m^2)
c	specific heat at constant pressure (kJ/kg °C)
COP	coefficient of performance (–)
E	total energy supplied to tap water by the system (kJ)
G	volumetric flow rate (m^3/s)
h_i	heat transfer coefficient for inside flow (W/m^2 K)
h_o	heat transfer coefficient for outside flow (W/m^2 K)
K	heat transfer coefficient (W/m^2 K)
l	length of the refrigerant tubes per loop (m)
n	quantity of the refrigerant loops (–)
P	power consumption (kJ)
Q	heat provided to tap water by the water pre-heated loops (kJ)
R	the diameter of the refrigerant tube (mm)
t	the shower duration (min)
T_1	temperature of incoming tap water (°C)
T_2	shower water temperature (°C)
T_{w1}	mean water temperature in HWT at the start of the experiment (°C)
T_{w2}	mean water temperature in HWT at the end of the experiment (°C)
ΔT	temperature difference between the refrigerant and SDW (°C)
V	volume of the hot water tank (L)

Greek letters

ρ	water density (kg/m^3)
δ	thickness of the copper pipe
λ_p	heat conductivity of the copper

Subscripts

com	compressor
ele	electrical heater
sum	in total
w	water

evaporator with defouling function for a WWSHP. Jorgen [15] analyzed the influence of different drain water flow profiles on the performance of a heat pump base inline heat recovery system, and the results showed that this type of heat recovery system was possible to recycle a large portion of heat in the drain water if appropriately sized.

Notwithstanding the SDW was regarded as a suitable heat source for heat recovery system, much of the energy consumed in SDW was wasted to the drainage system in real situations [16,17]. Recently, the research on using heat pump to recover waste heat from SDW water increased [18,19]. Compared with the SAHPWH and AHPWH, the heat pump water heater assisted with SDW has the advantages that the heat source was stable and the performance was not influenced by the changing weather and season [20]. In addition, because the inflow of cold water and the outflow of hot drain water occurred simultaneously, it allowed for useful quantities of heat exchange to take place.

On the other hand, most of the researches were focused on the large centralized users like public shower facilities, hotels etc [21,22], while only a limited number of investigations were aiming at small single families. For heat recovery from SDW in small single family, Wong [23] put forward a way to pre-heat the cold water by installing a simple single-pass counter-flow heat exchanger beneath the shower drain. The results indicated that 5–15% of shower water waste heat can be recovered, and waste water temperature can be reduced by 5.0–8.0 °C. McNabola and Shields [16] developed a SDW heat recovery system in horizontal domestic shower drains, which had an approximately 25% energy recovery efficiency.

As the form of the aforementioned systems using for small single family was relatively simple, and the temperature of SDW leaving the shower bath was still high, it could not make full use of the energy in SDW. To improve utilization efficiency of the waste heat in SDW, a novel heat pump water heater for shower (HPSWH) assisted with SDW was proposed in this paper. The novel heat pump water heater could recover part of waste heat from SDW with the water pre-heated loops before recovering most of the waste heat by heat pump cycle. In addition, a large portion of electricity could be saved compared to traditional electrical heater. And compared with large systems (city waste water), it has the advantages that the system is easier for installation and heat loss for delivering the water in large systems could be avoided. Firstly, a prototype of the HPSWH system was set up and a detailed design of the WHED presented. Secondly, the experimental procedures were described precisely. Thirdly, detailed analysis and evaluation on the experimental results were delineated. Finally, the energy savings and economic benefits were also discussed. The results from this study may serve as a reference for designing or evaluating heat pump water heater assisted with SDW in small single family.

2. Experimentation

2.1. Description of the experimental prototype

The schematic of the HPSWH system and the experimental setup are shown in Figs. 1(a) and (b), respectively. The system was mainly composed of a waste WHED, a compressor, a hot water tank (HWT), an electrical heater, a water mixing valve, and a capillary tube. Besides, the thermal insulation of the HWT was indispensable to improve its performance and R134a was chosen as refrigerant.

As shown in Fig. 1(a), the light lines denotes the water tubes while the dark lines designates the refrigerant tubes. When showering, the incoming tap water was firstly pre-heated by the SDW, and hence part of the waste heat was recovered when the SDW passed through the WHED, which was installed under the user. After pre-heated in the WHED, the tap water was divided into two paths. In one path, the water was heated by R134a in the HWT. While in the other path, the water was introduced into the water mixing valve to regulate the shower water temperature.

For the refrigerant, it absorbed the waste heat of SDW in the WHED, which was regarded as the evaporator. Then it was compressed and then released the heat to water in the HWT which served as condenser. Afterward, it was throttled by the capillary tube and back to the WHED. When the water temperature in the HWT was too low to take a bath, the electrical heater was started up to raise the water temperature.

To evaluate the performance of the novel heat pump water heater assisted with SDW, a prototype was built. The evaporator capacity was designed to be 2.70 kW based on the temperature and mass flow rate of SDW. The input power to the compressor and the condenser capacity were calculated to be 0.60 kW and