Energy 93 (2015) 1394–1403

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Experimental investigations on using phase change material for performance improvement of storage-enhanced heat recovery room air-conditioner

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ARTICLE INFO

Article history:
Received 11 June 2015
Received in revised form
19 September 2015
Accepted 15 October 2015
Available online 6 November 2015

Keywords:
Phase change material
Heat recovery
Air-conditioner
Space cooling
Water heating
Energy performance

ABSTRACT

The use of SEHRAC (storage-enhanced heat recovery room air-conditioner) for space cooling and free water heating has been confirmed effective but its overall performance will unavoidably be affected by the associated increase in water temperature in the heat recovery water tank. Measures to enhance the heat storage capacity of the water tank will thus be beneficial to the overall performance of SEHRAC. But virtually none has been done to date. For achieving this objective, the use of PCM (phase change material) in the water tank was proposed in this study. A prototype SEHRAC integrated with an expanded graphite/paraffin composite PCM was designed and setup in a test facility for laboratory experiments. Two identical sets of experiments with and without the use of PCM (wPCM and woPCM scenarios) under a range of outdoor temperature conditions were conducted. It was found that the wPCM scenario, as compared to the woPCM scenario, the overall coefficient of performance was 6.9%–9.8% higher and the heat retention time of the tank water was 21.1% longer. The results confirmed that the performance of SEHRAC could be improved by the use of PCM.

1. Introduction

Air-conditioners function to remove heat from indoor spaces and subsequently discharge this heat to the outside. The discharged heat, if recovered for water heating, can reduce energy use and greenhouse gas emissions. Along this line, HRAC (heat recovery room air-conditioner) was invented in the eighties for providing simultaneous space cooling and water heating [1]. Its energy saving potential and payback period were found attractive [2]. However, due to the possible heat supply and demand mismatch, recent research advocates the use of a water tank as an energy reservoir for heat recovery, leading to the evolvement of SEHRAC (storage-enhanced heat recovery room air-conditioner). When employed in residential buildings, SEHRAC is often used to recover and store the nighttime discharged heat for satisfying the daily water heating demand of a household.

Many simulation and experimental investigations have been done on SEHRAC. On simulation investigations, a study by the authors confirmed the effective use of SEHRAC for households in a typical residential area in Hong Kong [3]. A similar study was also carried out by Shimoda et al. [4] in Japan. Techarungpaisan et al. [5], based on fundamental principles of heat transfer, thermodynamics and fluid mechanics, developed a detailed mathematical model for SEHRAC. The model was coded into a simulation program and was used for system optimization. Yokoyama et al. [6] developed another mathematical model to relate the energy performance of SEHRAC with the outdoor air and tank water temperatures. Apart from mathematical models, recent research focuses on incorporating SEHRAC with other control devices to enable its efficient operation [7,8].

On experimental investigations, Ying et al. [9] examined the overall performance of SEHRAC and found that it was more efficient than electric water heating with an energy efficiency ratio of 1.2. Jiang et al. [10] found that SEHRAC could operate satisfactorily and the associated savings in water heating energy use were evident. Similar conclusions were also drawn by Monerasinghe et al. [11]. The energy performance, as compared to conventional air-conditioners, was examined by the authors [12]. It was reported that, for a typical household in Hong Kong, the use of SEHRAC could reduce the annual water heating energy use by 49%. In another study by the authors [13], the use of capillary tube and TEV

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http://dx.doi.org/10.1016/j.energy.2015.10.053

Nomenclature

c_p	specific heat capacity (kJ/kg K)
C	regression coefficient
COP	coefficient of performance
h	specific mass enthalpy (kJ/kg)
H	heat storage capacity of the water tank (MJ)
m	mass flow rate (kg/s)
M	mass (kg)
P	pressure (Pa or MPa)
Q	space cooling/water heating capacity (kW)
t	temperature (°C)
T	absolute temperature (K)
w	moisture content (kg/kg dry air)
W	power consumption (kW)
x	refrigerant vapor content (kg/kg)
Greek symbol	
α	time spent for the entire experiment
λ	latent heat of fusion (kJ/kg)
σ	latent heat of vaporization (kJ/kg)
τ	operating time
φ	relative humidity
Subscript	
a	air
b	atmosphere
cd	compressor discharge
cl	space cooling
cs	compressor suction
ei	evaporator inlet
er	evaporator return
es	evaporator supply
hi	heat exchanger inlet
ho	heat exchanger outlet
oa	overall
p	PCM
pa	paraffin
r	refrigerant
sl	saturated liquid refrigerant
sw	saturated water vapor
w	water
wh	water heating

(thermostatic expansion valve) as expansion devices in SEHRAC were side-by-side compared. It was identified that TEV was a more suitable option for its better refrigerant flow control during the heat recovery process.

The above studies have confirmed the effective use of SEHRAC for space cooling and free water heating, but it has been acknowledged that the associated increase in tank water temperature will unavoidably affect the cooling and heating performances of SEHRAC [11–13]. Therefore, measures to enhance the heat storage capacity of the water tank will be beneficial to the overall performance of SEHRAC.

For achieving this objective, the use of PCM (phase change material) in the water tank is proposed in this study. PCM is capable of storing and releasing large amounts of energy when charging and discharging. During charging, the material changes from solid to liquid and vice versa for discharging. As reported, PCMs can typically store 5–14 times more energy per unit volume than water [14]. The phase change characteristics also allow heat storage or release at an almost constant temperature. PCMs thus have been widely investigated for applications in various heat recovery systems [15,16] and systems adopting natural cooling sources [17].

For SEHRAC, the benefit of using PCM with a high energy storage density is twofold. First, its overall performance can be improved with the heat storage capacity of the water tank enhanced by PCM charging. And when it is not operating, PCM discharging can partially offset the heat loss from the water tank to better maintain the hot water at desired temperature.

The temperature of hot water for direct residential use often ranges between 35 °C and 50 °C [18]. There are a number of PCMs with phase change temperatures within this range; namely salt hydrates, fatty acids and paraffin waxes [19]. Among them, paraffin waxes are considered the most suitable option for domestic hot water applications owing to their non-toxicity, wide availability, low cost and non-corrosive property [20]. But as paraffin waxes are of extremely low thermal conductivity, recent studies are investigating the use of different heat transfer enhancement techniques to shorten the charging and discharging processes [21]. The techniques include insertion of a metal matrix into paraffin, dispersion of metallic particles, using paraffin containers augmented with fins, microencapsulation of paraffin, and impregnating paraffin into a high thermal conductivity material with porous structure.

Despite the potential benefits, there is virtually no study to date that integrates the use of SEHRAC and PCM. To confirm and quantify the performance improvement for their integration, a prototype SEHRAC was designed and setup in a test facility for laboratory experiments. Two identical sets of experiments with and without the use of PCM (abbreviated as wPCM and woPCM scenarios) under a range of outdoor temperature conditions were conducted. In the experiments, the operating parameters on the refrigerant, air and water sides of the system were closely monitored. Based on the experimental results, the heat storage capacity of the water tank, the refrigerant side operation characteristics as well as the space cooling, water heating and overall energy performances were examined and compared for the two scenarios.

Given the small equipment capacity due to residential use and the highly volatile refrigerant properties, monitoring of the refrigerant side performance is difficult. Thus the results presented in this study and the experimental protocol established will be useful for further development of SEHRAC.

2. Experimental study

2.1. Test facility

The experiments were carried out in a test facility located at the Hong Kong Polytechnic University. It comprised two environmental chambers resembling indoor and outdoor conditions. Each chamber measured 3.9 m in length, 3.8 m in width and 2.2 m in height, which was constructed in conformity with ASHRAE Standard 16 [22] for rating of room air-conditioners. Given the same test facility was used in earlier studies by the authors on performance evaluation of SEHRAC [12,13], to avoid duplication, only brief descriptions are given below.

The two chambers were completely insulated and separated. The outdoor chamber was conditioned by a BIACS (built-in air-conditioning system) and was provided with a set of sensible and