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Reliability verification of a solar–air source heat pump system with PCM energy storage in operating strategy transition

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ABSTRACT

In the recent decade, with solar energy assisted heat pump systems have increasingly developed. In the previous studies, a hybrid air source heat pump (ASHP) system was proposed, which coupled with latent heat thermal energy storage (LHTES) and solar thermal collector, for operating in various types of configurations. This paper describes the approach and principle for organizing the hybrid system in detail. Thereafter, a phase change material (PCM) based solar–air source heat pump (PCM-SAHP) prototype was set-up and implemented under variant testing conditions. Experimental results demonstrate that the PCM-SAHP system presented remarkable advantages on correcting the mismatch between supply and demand of thermal energy and electricity. Further, when the ambient temperature was higher than 38 °C, cooling COP of the hybrid system enhanced by 17%, compared with that of ASHP system under same surroundings. During the days that outdoor air temperature was below −10 °C, heating COP of the PCM-SAHP system rose by 65% comparing with that of ASHP system. In additional, switching operating strategies during system running will scarcely result in the violent or continuous fluctuations on the operating parameters. Therefore, the efficiency of the PCM-SAHP systems can be improved with capacity lapse avoiding, and exhaust controlling as well.

1. Introduction

Recent two decades, a growing number of individuals and communities incline space heating and cooling by heat pumps (HP) rather than conventional boiler system paralleling air conditioning (AC) system on account of higher energy efficiency and milder environment impact. Advanced cycle designs, improved cycle components and expanded cycle applications are the main development channels in HP technology [1]. Recently, latent heat thermal energy storage (LHTES) within HP system for space/water heating and cooling has received increasingly interests because of the flexibility, efficiency and stability through charge and discharge of thermal energy [2].

Phase change material (PCM) within passive heat storage building may be the simplest application for LHTES. PCM thermal board (PCMTB) and PCM thermal shield (PCMTS) can balance thermal energy substantially inside building [3–6]. Building structure, orientation, situated climatic region, as well as thermal property of building affects the effect of PCMTB and PCMTS [7,8] subtly. Active and-or passive heat storage with PCM for AC do not only slash energy consumption but improve adaptability of PCM [9–11]. Yet application of PCM defrosting reflects a brilliant improvement in system overall efficiency versus lower investment [12]. On the other hand, free cooling technique shows a nice potential in energy saving, efficiency enhancement and environment friendliness [13–16]. However ice storage might be a longer historical technology, which recently focuses on improving synthetic energy efficiency for the whole system [17–20]; by contrast, PCM with higher phase transition temperature within AC/HP seems more promising to rise evaporating temperature, therefore the optimistic capacity and efficiency can be anticipated [21,22]. On the other lens, PCM within AC for condensing heat recovery seems flexible, efficient and convenient [23,24] also. Actually, applications of PCM for residential cooling and heating are much more than that.

This paper presents a PCM based hybrid solar–air source heat pump (PCM-SAHP) system for building cooling and heating applications. Basic design concept, structure and components, and

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operating principle of the PCM-SAHP system are described prior. Sequentially, a testing prototype are organized and produced. Then details of testing methods and materials are serviced. Finally, performance of the system proposed during typical conditions are proposed and discussed; reliability and stability of that at the instant of operating strategy transition is carried out additionally. Experimental performances include compressor power consumption, cooling and heating capacity and COP, as well as temperature features of PCM in the LHTES facility.

2. Methods or materials

2.1. The prototype of the PCM-SAHP system

A PCM-SAHP system consists of four elements: ASHP, solar thermal collector, the triplex tube heat exchange (TRTHE) system encompassing PCM, as well as data acquisition and control sector. Briefly, this hybrid system could charge chilled energy in the TRTHE system during cool summer night with profit of the special discount tariff in electricity, and discharge chilled energy from the TRTHE system during peak energy period with high ambient temperature. Further, during low temperature days, this coupled system can store heating energy in the TRTHE system with solar thermal energy assisted and supply hot water or air, which avoids decrease in both heating capacity and COP, and refrains from increasing in compressor pressure ratio the ASHP system suffering. Therefore, the PCM-SAHP system could charge and discharge cooling/heating energy by a same facility, TRTHE which is the key component of the PCM-SAHP system.

Details about the system and TRTHE were presented in literature [25,26]. Niu et al. primarily presented the TRTHE system based PCM-SAHP system. And feasibility of the TRTHE system within compression vapor cycle has been proved. Schematic diagram of the PCM-SAHP system and structure of the TRTHE unit is shown in Fig. 1, while Specifications of the prototype are listed in Table 1. In this study, the TRTHE units and a prototype of the PCM-SAHP system are redesigned and organized. Additionally, nine operating modes and corresponding ten groups of tests for building cooling and heating are projected and implemented.

The TRTHE units within PCM-SAHP systems can fulfill nine operating modes, including space cooling by ASHP mode (M1), cold storage mode (M2), space cooling by TRTHE mode (M3), space cooling by TRTHE assisting ASHP mode (M4), space heating by ASHP mode (M5), heat storage mode (M6), space heating by TRTHE mode (M7), space heating by TRTHE assisting ASHP mode (M8) and space heating by TRTHE with solar hot water assisted mode (M9). All of these modes are listed in Table 2. During the summer night the hybrid system charges chilled energy into the TRTHE system using off-peak electricity (M2). When the cooling load of chamber is lower, the TRTHE system can provide stable chilling water for space cooling without compressor operation (M3). In the highest cooling load environment, the TRTHE system assists ASHP to serve for space cooling (M4). In winter, on the days of cloud or rain/snow free, solar hot water (about 30 °C) from the solar thermal collector stores heat into the TRTHE units that service as the low grade heat source for the heat pump system to avoid awkward performance of the ASHP system under low ambient temperature surroundings. Moreover, the TRTHE units within PCM-SAHP systems just perform as an evaporator in the compression vapor cycle, which eases oil return in the refrigerant circulation.

The TRTHE unit is made up of three concentric copper tubes and PCM that embedded in the space where the inner tube and the medium tube encompassed. Refrigerant circulates inside the inner tube driving by compressor, and water passes through the space between the outer tube and the medium tube as heat transfer fluid

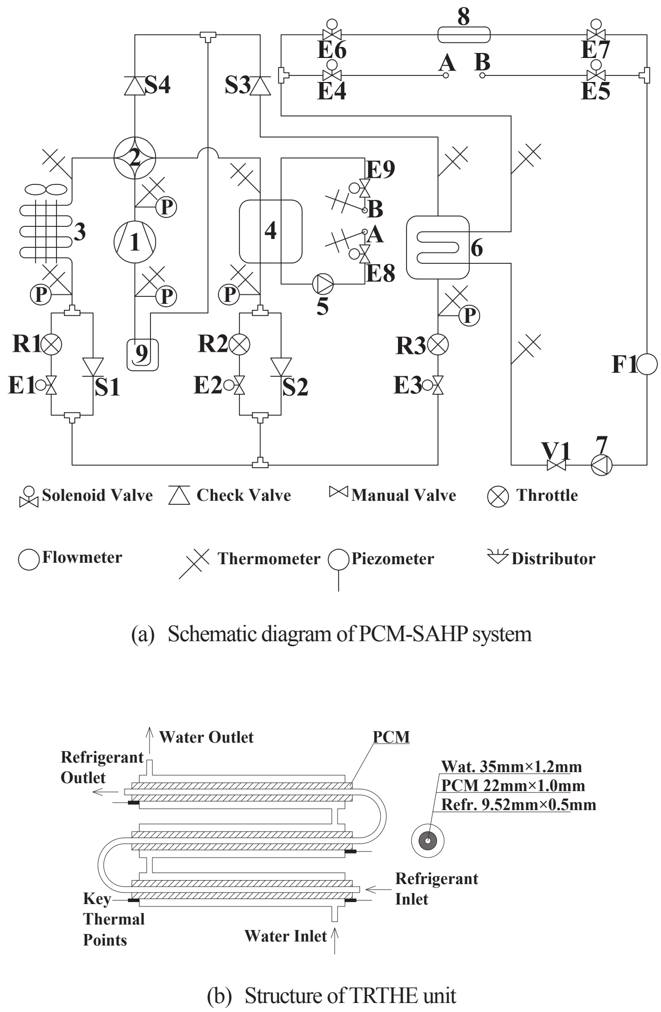

Fig. 1. Schematic diagram of PCM-SAHP system and structure of TRTHE unit.

(HTF). The material of RT5HC, as the PCM embedded in the TRTHE system was used in this equipment. Three concentric copper tubes are weld together after spinning process, and thermally insulated envelope was used to reduce heat loss.

Now, thermal energy storage capacity is the overriding parameter for the TRTHE system, which depends on the operating strategy of the hybrid system and the characteristics of air conditioning load for building. In this paper, a virtual building situated in Shanghai (China) was selected as the reference of air conditioning load and operating strategy for the devisal of thermal energy storage capacity in the TRTHE units, in where cooling/heating load is approximate balance in general buildings. According to the initial cost of equipments and the special discount tariff in Shanghai, partial thermal energy storage is appropriate, meaning that thermal energy discharge from the TRTHE system has a responsibility to eliminate part of thermal energy load during a whole day. At the beginning and end of space cooling season (less than 90 days) the percentage of cooling load to maximum value is about 30%, the TRTHE system can maintain thermal comfort level in chamber without any other chilled energy source operation from 10:00 to 18:00. On the other hand, during high ambient temperature days (about 100–120 days), the TRTHE units assisting ASHP system can discharge cooling energy from 10:00 to 18:00 to control the temperature and humidity in indoor space.