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Original article

Experimental study on performance of a solar-air source heat pump system in severe external conditions and switchover of different functions

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ABSTRACT

A phase change material (PCM) based solar-assisted air source heat pump (PCM-SAHP) composed of an air source heat pump (ASHP), a PCM unit, and a solar thermal collector is proposed. In this work, the system performance is experimentally tested in the severe external conditions, and the effect of switchover of different functions on the system stability is examined as well. The results indicate that a great improvement in both the system efficiency and heating/cooling capacity in the severely external conditions is achieved by the application of the PCM unit in the SAHP cycle. The outdoor air temperature throughout a whole day-night cycle has a significant effect on the system cooling performance. In contrast, the solar-heated hot water temperature, rather than the ambient temperature, exerts a great influence on the system heating performance. In order to maximize the system capacity and efficiency, how to match the capacity of the PCM unit and the compressor is crucial. In addition, the effect of switchover of different functions on the system stability is unapparent. Finally, the compatibility of the PCM unit with the SAHP system is concluded based on kinds of individual approach.

Introduction

Solar-assisted air source heat pump

Over the past two decades, solar-assisted heat pump (SHP) systems have been being widely utilized [1–4]. Of these, solar-assisted air source heat pump (SAHP) is the most promising system. In the numerical studies, Liang et al. [5] found that the system coefficient of performance (COP) tended to increase in proportion to the solar collector area. Liu et al. [6] noticed that the system heating capacity and COP was enhanced by 62% and 59%, respectively, compared with the air source heat pump (ASHP, under the same test conditions). Moreover, Zhu et al. [7] presented a dual-nozzle ejector enhanced cycle for SAHP. The simulation results showed that the COP could be improved by 34% over the conventional one. Recently, a report about the integrated photovoltaic-air source heat pump [8] announced that the energy saving ratio per unit investment for cooling and heating operation reached 41% and 35%, respectively.

PCM used in air-conditioner

Nonetheless, the characteristics of low energy flow density, intermittence, and instability of solar energy restrict its applications in heat pumps. In recent decades, phase change materials (PCMs) have increasingly been utilized in thermal energy charge/discharge for energy saving. Paraffin wax, a class of PCMs, has been widely used in many applications [9,10]. In recent years, various types of composite PCMs (included one-or-two type of PCM and other additive materials to improve the material properties) have been fully developed. As reported in the references [11–14], the composite PCMs had a higher thermal conductivity, a larger thermal energy storage capacity, and a wider temperature range. In a SAHP, these advantages may contribute to a stable and sustainable energy discharging flow, if the PCM is integrated into the SAHP.

Qu et al. [15] presented a so-called 'daily average collection efficiency'. When the efficiency of the solar thermal collector reached 50%, the maximum COP of the system could get up to 10. Real et al. [16] proposed an air-conditioner in which contained two types of PCMs. The PCM having lower phase transition temperatures was utilized in the cooling mode. And another PCM was utilized in the heating mode. The system energy efficiency ratio (EER) was found

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Nomenclature

AC	air conditioning
ASHP	air source heat pump
COP	coefficient of performance
$COP_{A\cdot C}$	cooling COP of ASHP
$COP_{A\cdot H}$	heating COP of ASHP
$COP_{C\cdot C}$	combined cooling COP in a cooling cycle (M2 + M4)
$COP_{T\cdot C}$	cooling COP of TRTHE in a cooling cycle (M2 + M3)
FTHE	finned tube heat exchanger
HP	heat pump
HTF	heat transfer fluid
LHTES	latent heat thermal energy storage
PHE	plate heat exchanger
$\dot{Q}_{A\cdot C}$	cooling capacity of ASHP, kW
$\dot{Q}_{A\cdot H}$	heating capacity of ASHP, kW
$Q_{A\cdot C}$	cooling capacity of ASHP, MJ
$Q_{T\cdot C}$	cooling capacity of TRTHE, MJ
TES	thermal energy storage
TRTHE	triplex tube heat exchanger
T_R	temperature of return water for space cooling or heating, K
T_S	temperature of supply water for space cooling or heating, K
$T_{R\cdot A}$	temperature of return water for ASHP, K
$T_{S\cdot A}$	temperature of supply water for ASHP, K
$T_{R\cdot T}$	temperature of return water for TRTHE, K
$T_{S\cdot T}$	temperature of supply water for TRTHE, K
V	volume flow of water for space cooling or heating, $m^3\cdot s^{-1}$
V_A	volume flow of water for space cooling or heating by ASHP, $m^3\cdot s^{-1}$
V_T	volume flow of water for space cooling or heating by TRTHE, $m^3\cdot s^{-1}$
V_O	volume of water for space cooling or heating, m^3
$V_{O\cdot A}$	volume of water for space cooling or heating by ASHP, m^3
$V_{O\cdot T}$	volume of water for space cooling or heating by TRTHE, m^3
$\dot{W}_{C\cdot C}$	compressor power consumption for space cooling, kW
$\dot{W}_{C\cdot H}$	compressor power consumption for space heating, kW
$\dot{W}_{C\cdot S}$	compressor power consumption for cooling energy storage, kW
$W_{C\cdot C}$	compressor power consumption for space cooling, kJ
$W_{C\cdot S}$	compressor power consumption for cooling energy storage, kJ
$c_{p\cdot w}$	specific heat at constant pressure, $kW\cdot kg^{-1}\cdot K^{-1}$
ρ	density of water, $kg\cdot m^{-3}$
τ	duration of cooling or heating, s
$\tau_{C\cdot C}$	duration of space cooling by TRTHE assisting ASHP, s
$\tau_{C\cdot S}$	duration of cooling energy storage, s
ΔT_w	temperature difference between supply and return water for space cooling or heating, K
$\Delta T_{w\cdot A}$	temperature difference between supply and return water for ASHP, K
$\Delta T_{w\cdot T}$	temperature difference between supply and return water for TRTHE, K

to be improved substantially. However, the system's volume had to be large enough to contain two types of PCMs. As a result, the system initial cost was increased. In addition, Fiorentini et al. [17] proposed a SHP which consisted of an air-based photovoltaic-thermal (PVT) collector, a PCM unit, and a reverse cycle heat pump. In this system, solar energy was utilized for heating. And in the nighttime, the system efficiency in the cooling energy storage mode was improved by the sky-background radiation.

Although a number of PCM based heat pump systems were studied, most systems separated the device of cooling energy storage from the device of heating energy storage. In order to reduce the initial investment of a PCM-based heat pump, the PCM unit should be cooling energy storage device and heating energy storage device as well. In Fig. 1 [18], the hybrid heat pump system can operate in both cooling and heating modes. In heating mode, the PCM unit as an evaporator increased the evaporating temperature. In cooling mode, it increased the input sub-cooling of the expansion valve (as a condenser). Obviously, the PCM unit operated at a relatively low temperature in heating mode, however, it worked at higher temperatures in cooling mode. Thus, it was difficult to determine the temperature scope of the PCM.

In Fig. 2 [19], the system consisted of a normal ASHP, a PCM unit, and a minor compressor with a relatively low compression ratio (Compressor II, Fig. 2). In this system, the high compression ratio can be reduced, and the phase transition temperature of the PCM was moderate (about 283.2–293.2 K, because the PCM unit only acted as the system condenser). However, in the heating mode, only part of the refrigerant flowed through the indoor heat exchanger. This may lead to occupant comfort complaints.

Objectives of this work

In this study, a PCM-SAHP system composed of an ASHP, a solar thermal collector, and a PCM unit is developed. As suggested by [20], the application of the PCM unit in the severe external conditions should be discussed especially. Thus, the objectives of this work include: (i) testing the system performance at severe ambient temperatures; (ii) examining the system characteristics in the unusual conditions; (iii) validating the system stability under switchover of different functions.

PCM-SAHP

In the proposed PCM-SAHP, the PCM is heated by the solar-heated hot water and cooled by the refrigerant. So that the triplex tube heat exchange units (TRTHE) are designed to be the PCM container. Fig. 3(a) illustrates the structure of the TRTHE unit. Table 1 presents the geometric characteristics. Because the TRTHE units are both the cooling and heating energy storage device, a type of PCM with appropriate phase transition temperatures is critical. Moreover, the latent heat of the PCM should be sufficiently large to minimize the gross volume of the TRTHE units. Thus, a type of composite PCM (based on the paraffin wax) named 'RT5HC' is selected and filled into the TRTHE units. Table 2 shows the PCM's thermodynamic properties. In addition, the composite PCM is validated as chemical inert with respect to most materials. Detailed design process of the TRTHE units can be found in a previous study [21].

Fig. 3(b) shows the schematic diagram of the PCM-SAHP. The system has nine operating modes, including (1) ASHP for space cooling mode (M1), (2) cooling energy storage mode (M2), (3) TRTHE units for space cooling mode (M3), (4) TRTHE units assisting ASHP for space cooling mode (M4), (5) ASHP for space heating mode (M5), (6) heating energy storage mode (M6), (7) TRTHE units for space heating mode (M7), (8) TRTHE units assisting ASHP for space heating mode (M8), and (9) TRTHE units with solar-heated hot water assisted for space heating mode (M9). Table 3 describes