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Investigation on system performance of air source heat pump water heater with phase change material

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Abstract

In this paper, a series of experimental tests on air source heat pump water heater (ASHPWH) using a novel heat battery module with phase change material (PCM) were carried out. The melting temperature of PCM is 58°C. Meanwhile special attention has been paid to the optimization of heat transfer in heat battery module by means of computational fluid dynamics (CFD). The results indicate that the instant coefficient of performance (ICOP) of ASHP is up to 3.82 but the operation of ASHP is unstable and in poor condition with a 1.3 mm caliber electronic expansion valve. The latest experiment shows that using 1.5 mm caliber electronic expansion valve can not only make ASHP run more smoothly but also increase ICOP to 4.08. During the discharge process of heat battery module, 106.5L domestic water can be heated from 15°C to 40°C. The CFD simulation testifies copper fins applied in heat battery module can greatly enhanced the heat transfer coefficient compared with aluminum fins.

Keywords: Heat pump water heater; phase change material; CFD; system performance

1. Introduction

With the rapid development of the economy to stimulate people's demands for high-quality life, water heaters have become an indispensable device in today's homes. Because of its characteristics of energy saving, high efficiency and comfort, ASHPWH has gradually been favored by domestic and foreign markets. China's ASHP industry has developed rapidly since the beginning of the 21st century. In the latest decade, China has become the world's second largest ASHP producer next to Japan. According to the statistical data in 2015, ASHPWH share in China is only 3%, but with the promulgation of relevant energy conservation policies and the improvement of consumers' environmental awareness, ASHPWH has unparalleled application prospect.

Some researches on ASHPWH have been conducted for several decades. For example, the host of ASHPWH needs frequent start and stop, which not only causes a large amount of energy waste but also greatly affects the life of the heat pump system, which will limit the further development of ASHPWH. However, PCM has the advantages of large latent heat and suitable phase transition temperature, which can replace the bulky water tank and further enrich the application scenario [1] of ASHPWH. Moreover, ASHPWH with PCM can make rational use of electric power cost between on-peak and off-peak, saving the cost of electricity and balancing the grid load.

Moreover, PCM has problems such as low thermal conductivity and unstable heat storage performance [2]. Therefore, strengthening the heat transfer of PCM in the endothermic and exothermic process has become a research focus of PCM. At present, the research on the application of highly conductive nanomaterials [3] coupled with PCM to improve the thermal conductivity of PCM has made significant progress. Motahar et al. [4] experimentally studied the thermal conductivity and viscosity of n-octadecane/TiO_2 nanoparticles [5-6] and found that the thermal conductivity is non-monotonic in both solid and liquid phases. In the solid phase, when the mass fraction of nanoparticles is 3%, the thermal conductivity increases the most. In the liquid phase, when

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the mass fraction of nanoparticles is 4%, the thermal conductivity increases the most. In addition, the maximum average thermal conductivity of the two stages was enhanced by about 5%.

The use of microencapsulated of phase change material (MPCM) [7-8] can be effective in reducing the reactivity of PCM with the external environment, increasing the heat transfer area and the heat transfer rate, which makes MPCM has great application potential in the fields of heat storage, temperature control and heat protection. Luo et al. [9] first applied the miniemulsion polymerization method to the synthesis of nanocapsule phase change materials, and prepared nanocapsules with paraffin as the core material, styrene and methyl methacrylate copolymer as the shell material [10-11]. The obtained nanocapsules have a complete core-shell structure and a particle size of less than 100 nm. Park et al. [12] also synthesized stable spherical nanocapsules with paraffin as core and polystyrene as shell by miniemulsion polymerization. The DSC freeze-thaw cycle shows that it has good thermal stability and exothermic properties, and the latent heat of phase change can reach up to 145 J/g.

When there is an electric current passing through the loop composed of different conductors, the endothermic and exothermic phenomena will appear respectively at the joints of different conductors with the direction of the current. Accordingly, Selvam et al. [13] used the Peltier effect [14] to enhance the heat transfer of PCM. Experiment has shown that the cold junction temperature of a PCM Peltier cooler under pulse operation is significantly reduced from -14.5°C to -17.5°C compared to a Peltier cooler without PCM under pulsed operation. It is also found that, there is no significant reduction in COP of the Peltier cooler under pulse operation with PCM as compared to pulse operation without PCM.

Therefore, the purpose of this study is to explore the feasibility and stability of the combination of ASHPWH and PCM by means of thermodynamic performance analysis. Based on the preliminary experimental work and the test data of the prototype, system performance of ASHPWH is analyzed. Moreover, the heat transfer optimization of heat battery module has been conducted via CFD simulation, the comparison between copper tubes and aluminum tubes is illustrated in this paper.

2. Experimental setup

2.1. ASHPWH with PCM experimental system description

The schematic diagram of present experimental setup is shown in Fig. 1. Its basic components include compressor, heat battery module, expansion valve and evaporator. In order to enhance the heat transfer process in battery module, CFD simulation is applied to optimize the structure of heat battery compared with traditional ASHPWH, the main difference is that the condenser is replaced by a heat battery module. Due to the confidentiality agreement with a partner company, the details of heat battery module are not available in this paper. As can be shown in Fig. 2, the superheated refrigerant vapor, which is produced in the evaporator, flows into the compressor and turns into high temperature and pressure refrigerant vapor via the isentropic compression process 1-2. Then the refrigerant undergoes an isobaric cooling process 2-3 to transfer heat to PCM in the heat battery module. The supercooled refrigerant flowing out from the heat battery is throttled by the expansion valve and turns into a gas-liquid mixed state. The refrigerant then re-enters a new cycle through isobaric evaporation process 4-1 in the evaporator. During the valley electric charge time, ASHPWH starts to work and provide heat. Most of the heat released by the refrigerant is stored in PCM in the form of latent heat. When the hot water is needed, the cold water flows into the heat battery module that absorbs a large amount of heat and becomes hot water that can be used immediately. The time of hot water demand is mostly in peak time period, because of the difference of electric price between the peak and the valley, it can reduce electricity costs.

The thermodynamic performance of ASHPWH with PCM can be calculated according to Fig.2. First of all, the mass flow in ASHP can be calculated through the volume flow of the compressor multiplied by the refrigerant density at compressor inlet. The specific calculation equation is as follows:

$$\dot{m} = \dot{V}_s \cdot \rho \tag{1}$$

In the actual compression process, the electric energy used to compress the refrigerant vapor can be calculated by the following equation (2).

$$W = \frac{\dot{m}(h_2 - h_1)}{\eta_o} \tag{2}$$

Then the released heat from the refrigerant R22 to PCM in the heat battery can be calculated by using the following equation (3).

$$Q_b = \dot{m}(h_2 - h_3) \tag{3}$$

The instant coefficient of performance (ICOP) of ASHP, which is defined as the ratio of heat release of refrigerant in heat battery to power consumption of compressor, can be calculated as follows:

$$ICOP = \frac{Q_b}{W} \tag{4}$$

In the above equation (1) ~ (4), $\dot{m}$ represents the mass flow rate of refrigerant R22. ρ and $\dot{V}_s$ stand for the density and volume flow of refrigerant individually. h_1, h_2, h_3 and h_4 stand for the enthalpy of point 1, point 2, point 3 and point 4 in Fig. 2 respectively. η_0 represents the overall efficiency of compressor. It is worth mentioning that the enthalpy and condensation temperature of refrigerant R22 can be obtained according to the measured temperature and pressure in the corresponding position.

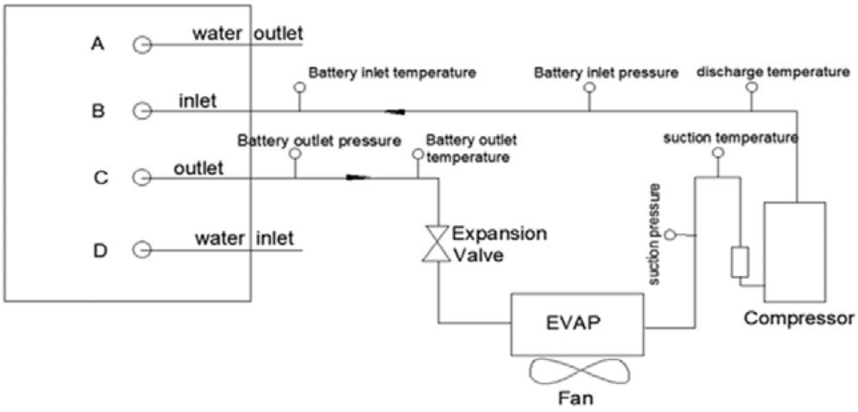


Fig. 1. Schematic representation of experimental setup

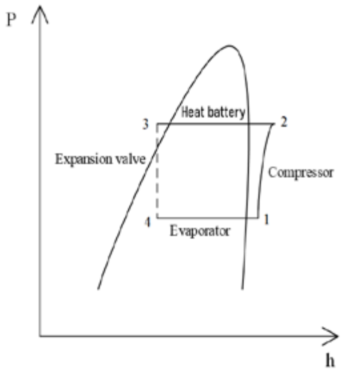


Fig. 2. Theoretical P-h diagram of ASHPWH with PCM

2.2. Testing procedure and measuring sensors

The main goal of these experiments is to test the stability and feasibility of ASHPWH using PCM. During the charge process, the refrigerant R22 releases the heat to the heat battery module whose initial temperature is about 20°C to a fully charged state. It can be measured that the dry bulb temperature and the wet bulb temperature of the ambient environment are 21°C and 19.5°C respectively. During the discharge process, 15°C cold water flows into the heat battery, and the obtained high-temperature hot water is mixed with 15°C cold water at the exit to obtain domestic hot water with 40°C. When the outlet temperature of water has reached 40°C without mixing with cold water, it is considered that the heat battery module is in a completely discharged state. The heat exchange capacity in the heat battery module can be calculated according to Equation (3), and the electric energy consumed by the compressor can be obtained due to the detected voltage and current. Accordingly, the system ICOP can be acquired by using Equation (4).

The performance parameters of the host are listed in Table 1. The experimental bench is shown in Fig. 3. It should be noted that the heat battery module is the most important part of the ASHPWH with PCM and the biggest difference from the traditional ASHPWH.

Table 1. Performance parameters of host of ASHP system

Parameters	Value
Rated heating capacity (kW)	3.2
Rated input power/current (kW/A)	0.88/4.2
Maximum input power/current (kW/A)	1.4/6.5
Refrigerant	R22
Rated charge volume (g)	1700
Caliber of electronic expansion valve (mm)	1.3/1.5

Fig. 3. Picture of the ASHPWH with PCM experimental bench.

As can be seen in Fig. 1, the experimental bench equips 4 thermocouples (suction temperature, discharge temperature, battery inlet temperature, battery outlet temperature), 3 pressure sensors (suction pressure, battery inlet pressure, battery outlet pressure). These sensors are used to measure the instantaneous change in refrigerant and to analyze the thermodynamic properties of the system. The specific information about these measuring sensors, such as the instrument type, measuring range and accuracy are given in Table 2.

Table 2. Major measuring sensors used in the experimental system

Parameter	Instrument type	Measuring range	Accuracy
P	diffused silicon pressure sensor	0-2MPa	±0.2% of MV
T	K-type thermocouple	0-1000°C	±1.5°C

3. Results and discussion

3.1. Experimental optimization

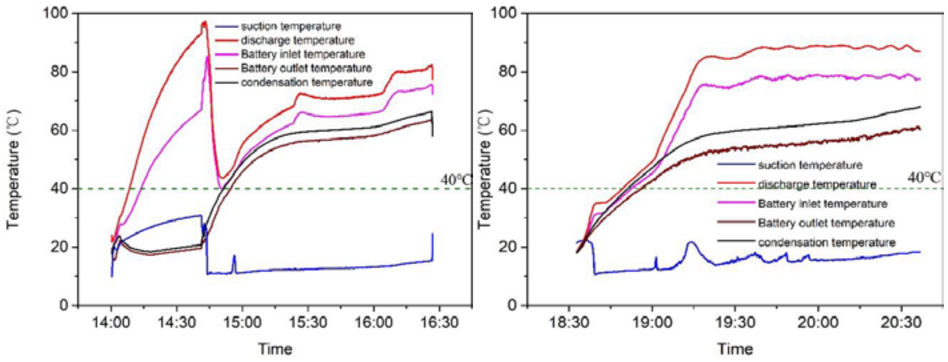
In the experimental investigation, the effect of two different calibers of expansion value on system performance has been studied, as shown in Table 3. The main performance parameters of the two experiments are shown in Table 4. The system thermodynamic performance of these two experiments are illustrated in Fig. 4 and Fig. 5. Due to the property of PCM, the temperature will not change when it is in a phase change state. Therefore, when the temperature of the refrigerant is constant, the PCM is approximately considered to be in a molten state. According to Fig. 4(a), in the first 45 minutes, the mass flow rate of the refrigerant is small and unstable, resulting in a sharp rise in discharge temperature and battery inlet temperature. When the PCM melts, the temperature and enthalpy of the heat battery inlet are 65°C and 423.3 kJ/kg respectively, and the enthalpy of heat battery outlet is 273.15 kJ/kg. The mass flow rate of refrigerant is calculated as 26 g/s, so the heat exchange capacity in the heat battery is 3.89 kW. The ICOP of the first experiment can reach 3.82. After the previous electronic expansion valve with a caliber of 1.3mm is replaced by that with a caliber of 1.5mm, the second experiment shows that using the electronic expansion valve with a caliber of 1.5mm can not only make ASHP run more smoothly but also substantially increase discharge temperature and battery inlet temperature. It can be calculated that the ICOP of the system is improved by 6.8% to reach 4.08. During the exothermic process of heat battery module, PCM heats 106.5 L water from 15°C to 40°C. It can be concluded that ASHPWH with PCM is feasible.

Table 3. Main parameters of the ASHP after the expansion valve is replaced

Case	Host	Refrigerant	Rated charge volume (g)	Caliber of expansion valve (mm)
1	Haipu (1p)	R22	1700	1.3
2	Haipu (1p)	R22	1700	1.5

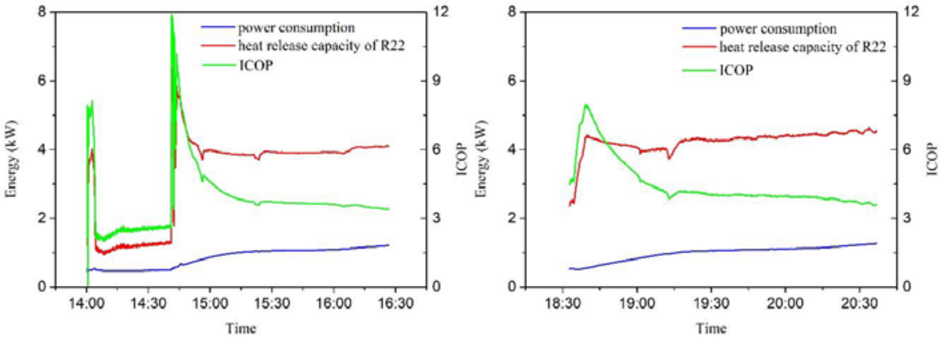
Table 4. Main performance parameters of the two experiments

Parameters	Case 1	Case 2
Discharge temperature (°C)	71	88
Battery inlet temperature (°C)	65	78
Battery inlet enthalpy (kJ/kg)	423.3	437.8
Battery inlet enthalpy (kJ/kg)	273.5	270.8
Mass flow rate (g/s)	26	25.8
Heat release capacity of R22 (kW)	3.89	4.34
ICOP	3.82	4.08
Hot water supply (L)	100	106.5



(a) system with the caliber of expansion valve of 1.3 mm (b) system with the caliber of expansion valve of 1.5 mm

Fig. 4. System temperature variation with different expansion valves



(a) system with the caliber of expansion valve of 1.3 mm (b) system with the caliber of expansion valve of 1.5 mm

Fig. 5. System performance variation with different expansion valves

3.2. Numerical simulation optimization

At present, one of the main problems of heat battery module is poor heat transfer effect, so enhancing the heat transfer between the PCM and refrigerant/water is the major optimization object. The structure of heat battery module used in this experiment is a fin-and-tube heat exchanger, in which the material of the fin is aluminum, and the material of the heat exchange tube is copper. Aluminum has a relatively good thermal conductivity with an acceptable price. It is one of the most commonly used materials for fin materials. However, when it is connected with a copper tube in heat exchangers, the contact thermal resistance between the two is not conducive to the heat exchange between the PCM and refrigerant/water. Therefore, the simulation analysis of the effect of using copper fins instead of aluminum fins on heat transfer in a heat exchange unit was carried out. The two center sections, as shown in Fig. 6, are selected for observation.

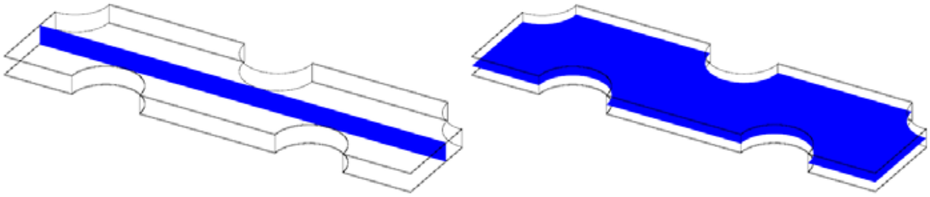


Fig. 6. Two center sections for observation

In the process of simulating the endothermic melting of PCM, in order to simplify the model, the boundary condition on the refrigerant side is set to a constant temperature of 346K, and the initial temperature of the phase change material is 293 K. The CFD simulation results are shown in Fig. 7 and Fig. 8.

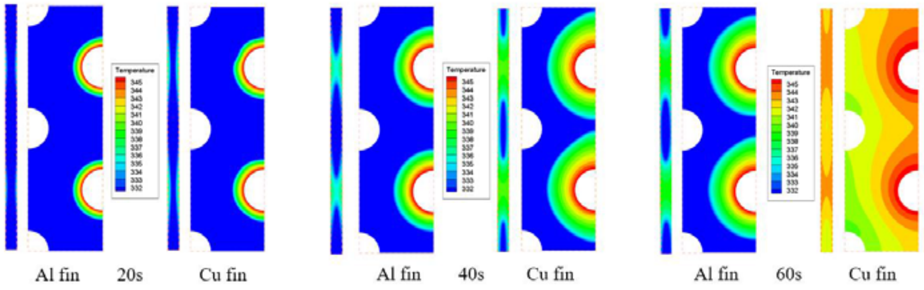


Fig. 7. Temperature distribution of two kinds of fins at different times

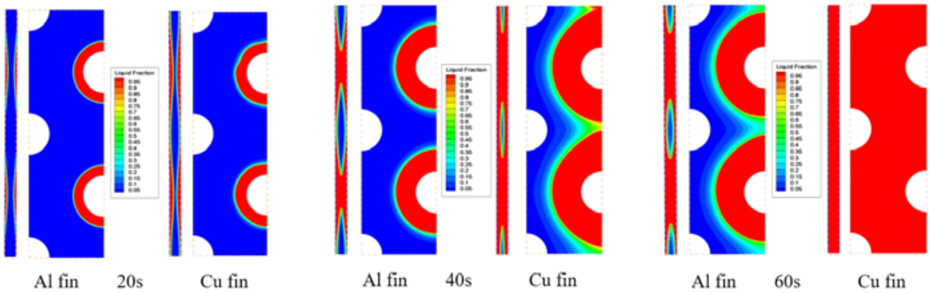


Fig. 8. Liquid fraction distribution of two kinds of fins at different times

It can be seen that the heating rate of PCM increases significantly when using copper fins in the heat battery module. When the heating time reaches 60 s, PCM in heat battery with copper fins almost turned into a liquid state, while a considerable part of PCM of that with aluminum fins was still in solid state. On the one hand, the copper fin can be completely welded together with the copper tube to effectively avoid the adverse effect of contact thermal resistance in heat transfer process; on the other hand, the thermal conductivity of copper is much higher than that of aluminum. Therefore, the use of copper fins can further reduce the thermal resistance of heat transfer and enhance the heat transfer coefficient between the fins and PCM. However, the price of copper is higher than that of aluminum. It is conceivable to replace some of the fins with copper fins to reduce the cost burden.

4. Conclusions

In this paper, a series of experimental tests on a novel heat battery module with PCM applied to ASHPWH were carried out. Based on the preliminary experimental work and the test data of the prototype, the integrated system performance is analyzed. In order to enhance the heat transfer process in battery module, CFD simulation is applied to optimize the structure of heat battery. The following conclusions can be drawn:

1. From the theoretical analysis and experimental results, in the first experiment, the ICOP of ASHP is up to 3.82 but the operation of ASHP is unstable and in poor condition. After the previous electronic expansion valve with a caliber of 1.3 mm is replaced by that with a caliber of 1.5 mm, the latest experiment shows that using 1.5 mm caliber electronic expansion valve can not only make ASHP run more smoothly but also increase ICOP by 6.8% to 4.08. It indicates that ASHPWH with PCM system has a good application prospect and is feasible for practical application in production activities.
2. Copper fins can effectively avoid the adverse effect of contact thermal resistance and greatly enhance the heat transfer coefficient between PCM and refrigerant/water according to the CFD simulation. Considering that copper is more expensive than aluminum, it is conceivable to replace some of the fins with copper fins to balance the cost burden and heat transfer efficiency of heat battery module.

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Responses to Reviewers' Comments

Dear Editor and Reviewers,

We quite appreciate the comments concerning our manuscript entitled "Investigation on system performance of air source heat pump water heater with phase change material". Those comments are all valuable and very helpful for revising and improving our paper, as well as the important guiding significance to our researches. We have studied comments carefully and have made correction which we hope meet with approval. Revised portion are marked in red in the paper. The main corrections in the paper and the responses to the reviewer's comments are written in blue as following:

Reviewer #1

This paper made experimental tests on air source heat pump water heater (ASHPWH) using a novel heat battery module with phase change material (PCM), and CFD simulation testifies copper fins applied in heat battery module. It is a good topic to explore the feasibility and stability of the combination of ASHPWH and PCM. The content of the paper is well-organized and the quality of the English is satisfactory. The author clearly explains the experimental setup, analysis of experimental and simulation results. Acceptance of this paper after minor revision is reasonable.

1) Would you please add some detailed description of the specifications of heat battery module with PCM used in the paper?

Discussion: Thanks very much for reviewer's suggestion. We deeply agree with the reviewer. However, the detailed information of heat battery module with PCM is inconvenient to provide in the paper due to the confidentiality agreeement with a partner company. Accordingly we have made the explanation in section 2.1.

Reviewer #2

1) In Table 1 and 3, Has caliber of electronic expansion valve unit? It's better to supply it.

Discussion: Thanks very much for reviewer's careful suggestion. The unit of caliber of electronic expansion is **mm**. According to the reviewer's advice, we have supplemented the unit of caliber of electronic valve in Table 1 and 3. Moreover, the corresponding text has also been modified and marked in red.

We tried our best to improve the manuscript and made some changes in the manuscript. We appreciate for Editors/Reviewers' warm work earnestly, and hope that the correction will meet with approval.

Once again, thank you very much for your comments and suggestions!

Naiping Gao