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Charging properties of a compact energy storage device for transport air conditioning applications

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Abstract

Air conditioning system in transport applications is a great challenge due to the frequently fluctuated load which causes comfort degradation and even healthy concern. In our previous study, a compact energy storage device filled with PCM was designed and experimentally tested which showed great potential for thermal comfort improvement and efficiency improvement. In this study, charging properties of the energy storage device for train air conditioning systems are experimentally investigated. Time evolutions of PCM temperature during the charging process are presented. The charging performances including charging time, transient charging rate, thermal efficiency and exergy efficiency are revealed. The results show that the designed device has excellent heat transfer behaviors with exergy efficiency up to 78%. The designed device is feasible to be used in transport air conditioning systems due to the quick charging.

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Keywords: PCM; energy storage; air conditioning; energy and exergy analysis

1. Introduction

Unlike the buildings, the operating conditions of transport air conditioning systems are more challenging due to its fast-changing ambient. The passenger load is always flexible and the peak load can surpass 30% of the designed condition [1]. Besides, fluctuated cooling load caused by air infiltration will lead to the frequent change of the output power of the compressor [2]. As a result, the traditional air-conditioning systems will not be sufficient to respond to

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the load changes. This will cause comfort degradation and low system efficiency. Hence, an effective method is urgently needed to smooth the cooling load for thermal comfort improvement and energy savings.

Latent heat thermal energy storage systems (LHTESS) based on phase change materials (PCMs) have been widely used to handle the unbalance between energy demand and supply [3-5]. The large energy storage capacity at a relatively constant temperature is particularly attractive for solving the fluctuation problem of transport air-conditioning systems. Attempts using LHTESS to settle the mismatch issues in air conditioning systems have been made. Previous research showed, when integrating LHTESS with traditional air conditioning system, the system efficiency could be improved. Zhao et al. [6] proposed a PCM energy storage system used in water-cooled air conditioning systems. The results showed that COP of the integrated system can be increased by 25.6%. Hence, it is feasible and attractive to employ LHTESS to deal with the frequent load fluctuation issues.

For the LHTESS, charging is a great challenge. Due to the relatively low thermal conductivity of PCMs, the charging rate and efficiency is always insufficient to meet the real applications, especially for the transport air conditioning systems. This is due to that, for the existing transport air conditioning systems, air is used as the heat transfer fluid, which has lower heat transfer coefficients. Hence, investigations on the charging behaviors including the heat transfer enhancement of LHTESS used in transport air conditioning applications are essential.

In previous research, various kinds of methods had been used to improve the heat transfer performance of LHTESS. Al-Abidi et al. [7] used fins for PCM melting in a triplex tube heat exchanger and shortened the total melting time by 34.7%. Research by Xiao et al. [8] showed that nickel and copper foam can increase the thermal conductivity of the PCM by nearly 3 times and 15 times respectively. Among the existing enhancements, adding fins are very attractive and effective [9,10].

The transport air conditioning system has a strict requirement of weight and space. Hence, in this study, a compact energy storage device using fins is designed and manufactured. To the best of our knowledge, there is still no comparable approach to investigate the charging behaviors of such a device, especially using cold air as the charging medium. The charging properties of the energy storage device are experimentally investigated. Time evolutions of PCM temperature during the charging process are presented. The charging performances including the charging time, transient charging rate, thermal efficiency and exergy efficiency are revealed.

2. Experimental setup

2.1. Phase Change Material

Table 1. Thermal-physical properties of PCM

Latent heat	220 kJ/kg
Melting range	17-19 °C (18 °C)
Congeeing range	19 -17 °C (17 °C)
Specific heat capacity	2 kJ/(kg·K))

2.2. Experimental rig

Thermal properties of the PCM including latent heat, phase change temperature and specific heat capacity were measured using a differential scanning calorimeter (DSC-2, Mettler Toledo) which are shown in Table1.

In order to test the heat transfer characteristics of the compact energy storage device, an experimental testing system was set up which is shown in Fig. 1.

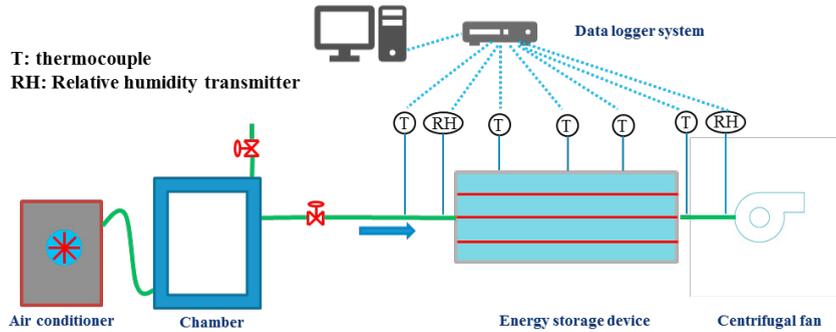


Fig. 1 Schematics of the experimental rig for testing the energy storage device

K-type thermocouples (0.3 % accuracy) were fixed at the inlet and outlet of the device and distributed inside the PCM. RH & T transmitters (3.0 % accuracy) were used to measure the inlet and outlet air relative humidity. A thermal anemometer (1.0 % accuracy) was employed to measure the inlet air velocity.

3. Performance indexes

3.1. Charging rate

Charging rate of the energy storage device, r_a , is the amount of cold energy released by the air, and could be calculated as follows.

$$r_a = \dot{m}_a \left(\sum_0^t h_{a,out} - \sum_0^t h_{a,in} \right) \quad (1)$$

where, \dot{m}_a is the average mass flow rate of air; t is the time; $h_{a,in}$ and $h_{a,out}$ are the inlet and outlet enthalpy of air respectively.

3.2. Charging thermal efficiency

The charging thermal efficiency, η_t , is defined by Eq. (2).

$$\eta_t = \frac{Q_{PCM} + Q_{Al}}{Q_a} \quad (2)$$

where, Q_{PCM} and Q_{Al} are the total energy absorbed by PCM and the frame of the energy storage device, respectively. Q_a is total energy released by air.

3.3. Charging exergy efficiency

The charging exergy efficiency, η_e , is defined by Eq. (3).

$$\eta_e = \frac{E_{PCM} + E_{Al}}{E_a} \quad (3)$$

where, E_{PCM} and E_{Al} are the total exergy absorbed by PCM and the frame of the energy storage device, respectively. E_a is total exergy released by air.

4. Results and discussion

4.1. Time evolution of PCM temperature

Fig. 2 shows the temperature distribution of PCM in the air flow direction. When time is at 125 s, the PCM with the axial distance of 50mm begins to freeze, while PCM with longer axial distances remains in superheating; when time is above 235, 315, 455 and 550 s, the PCM with axial distances of 100, 150, 200 and 250 mm starts to freeze respectively. When time increases to 1275 s, PCM at 50 mm becomes solid totally which indicates the complete charging. PCM with other axial distances finishes charging at 2100, 2900, 3420 and 3775 s respectively.

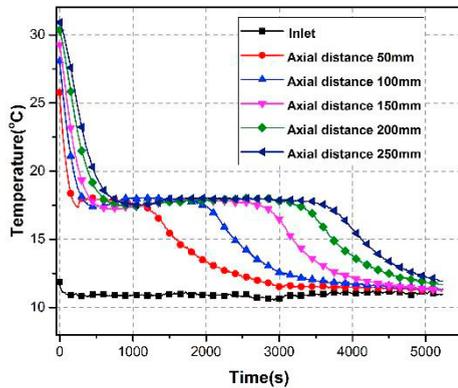


Fig. 2 Time evolution of axial temperature of PCM with inlet temperature and velocity at 11 °C and 0.70m/s

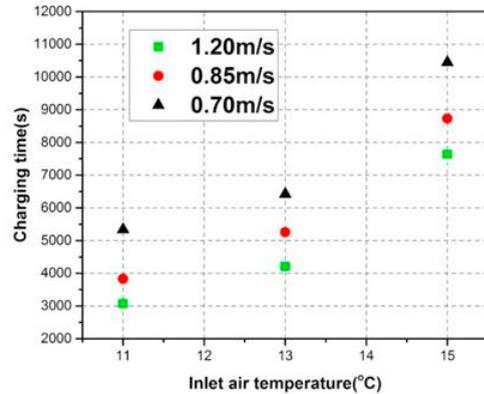


Fig. 3 Charging time with different inlet air temperature and velocity

4.2. Charging time

Charging time is a parameter showing how long the energy storage device can be fully charged. Fig. 3 illustrates the variations of charging time with different inlet air temperatures and velocities. In general, higher inlet air temperature or lower velocity will increase the charging time. When the air velocity is 0.7 m/s, as inlet air temperature decreases from 15 to 11 °C, charging time decreases gradually from 10450 s to 5340 s. This is due to the fact that higher temperature difference of heat transfer will lead to larger heat transfer capacity, and correspondingly cold energy of the air will be stored in the PCMs faster. As inlet air temperature is 15 °C, when air velocity increases from 0.7 to 1.2 m/s, charging time decreases generally from 10450 s to 7635 s, which results from the increase of heat transfer coefficient.

4.3. Charging rate

Charging rate is of great importance to the energy storage device, which reflects its heat transfer characteristics. Fig. 4 illustrates the transient charging rate under different inlet air temperature and velocity. For one given inlet air temperature, when air velocity increases, the steady charging rate goes up correspondingly, as shown in Fig. 4(a)-(b). When the inlet air temperature is 11 °C, the steady charging rate increases from 0.80 to 1.30 kJ/s as air velocity increases from 0.70 to 1.20 m/s.

With the inlet air velocity at 1.20 m/s and temperature at 15 °C, charging rate decreases sharply from 3.75 kJ/s and then keeps relatively stable at 0.62 kJ/s for 5020 s, as shown in Fig. 4(b). After that, the rate decreases until 0 kJ/s. At the beginning stage, the highest rate is due to the high temperature difference of heat transfer between air and PCM, and the stable rate indicates the phase change.

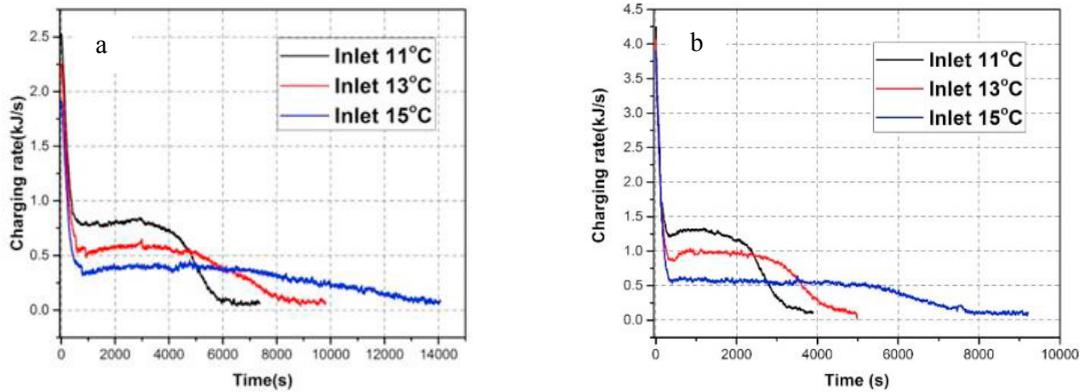


Fig. 4 Transient charging rate under different inlet air temperature (a: 0.70 m/s; b: 1.20 m/s)

4.4. Charging thermal efficiency

Table 2. Charging thermal efficiency

Inlet air temperature(°C)	Inlet air velocity(m/s)		
	0.70	0.85	1.20
11	72.91%	87.01%	84.72%
13	70.82%	82.22%	79.94%
15	66.74%	77.35%	71.98%

Charging thermal efficiency is a parameter that assesses thermal heat transfer and insulation

4.5. Charging exergy efficiency

Table 3. Charging exergy efficiency

Inlet air temperature(°C)	Inlet air velocity(m/s)		
	0.70	0.85	1.20
11	59.88%	77.92%	68.51%
13	66.09%	78.63%	70.57%
15	65.54%	78.16%	70.40%

Charging exergy efficiency presents the irreversible energy loss due to the temperature difference of heat transfer. Table 3. shows the influence of air velocity and temperature on exergy efficiency.

The obtained results show that for all the given

5. Conclusions

In this paper, the charging behaviours of a latent heat energy storage device using air as heat transfer fluid have

performance of the energy storage device, which is shown in Table 2. It could be seen that the charging thermal efficiency is quite high, which indicates good thermal heat transfer and insulation. For the velocity at 0.7, 0.85 and 1.2 m/s, the thermal efficiency for the given temperature range could reach 72.91%, 87.01% and 84.72%, respectively. The obtained results also show that when inlet temperature increases, the thermal efficiency drops. This is due to the longer charging time caused by higher inlet air temperature, leading to more cold loss to the ambient.

temperature, with the increase of inlet air velocity, the charging exergy efficiency performs an upward and then downward trend. For instance, The charging exergy efficiency increases from 59.88% to 77.92% and then decreases to 68.51% when the velocity changes from 0.70 to 0.85 and then 1.20 m/s for the given temperature at 11 °C. This is due to that at the given inlet temperature, the total air exergy is the product of the air specific exergy difference, air mass flowrate and charging time. Through higher velocity increases total air mass flowrate, it also leads to less charging time. Besides, the overall exergy efficiency for the given experimental conditions is relative high, with an average charging exergy efficiency at around 70%.

been experimentally investigated for transport air conditioning applications. Time evolutions of PCM temperature are shown. The charging performances including charging rate, charging time, thermal and exergy efficiency are disclosed.

The energy combined with exergy analyses reveal the designed device has excellent heat transfer behaviours with energy efficiency and exergy efficiency up to 87% and 78%, respectively. Besides, the obtained results show that both lower inlet air temperature and higher air velocity can shorten the charging time, with the minimum charging time of 3000 s in this study. The designed energy storage device is suitable for transport air conditioning applications due to its fast charging, high energy and exergy efficiencies. Prototypes based on the obtained results have been designed, and test results will be open in next publications.

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