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Experimental Study of A LTES Made By a Finned Heat Exchanger Immersed In a Paraffinic PCM

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Abstract **–**In this paper, a new Latent Thermal Energy Storage (LTES) system, made by a finned tube heat exchanger immersed in the commercial paraffinic Phase Change Material (PCM) RT44HC is studied experimentally. The storage capacity and the thermal performance of the LTES during both melting and solidification processes of the PCM was analysed for different test conditions using water as heat transfer fluid. In particular, experimental tests were performed by considering several values of hot and cold water temperature at the heat exchanger inlet, ranging from 55 to 70 °C and from 14 to 29 °C during charging and discharging processes, respectively. For each test, three different values of the water flow rate through the heat exchanger (25, 50, 100 kg/h) were considered. Results show how the thermal power increases considerably by charging (discharging) the LTES with higher (lower) inlet water temperature and with a higher water mass flow rate. For a fixed inlet water temperature and for growing flow rates, an increase in thermal power up to 1.16 kW occurs. For fixed flow rates, a thermal power increase of 49.5% is registered going from 50 to 70°C of the inlet water temperature. The thermal performance of the LTES are also compared with those obtained using pure water as heat storage material, outlining that the storage capacity of the system using PCM instead of water is increased of about 300-400%.

Keywords**:** Finned heat exchanger, PCM, latent thermal energy storage, experimental set-up, heat transfer, stored energy

1. Introduction

Energy systems driven by renewables require large thermal energy storages to minimize the limitation of the scarce simultaneity between energy production and demand. In this scenario, the use of Latent Thermal Energy Storage (LTES) systems, in which Phase Change Materials (PCMs) having a melting temperature range close to the specific interest, plays an important role to increase the thermal storage capacity per unit of volume. The major disadvantage of these materials in commercial applications is their very low thermal conductivity. To solve this problem, different solutions have been proposed in the literature to enhance the heat transfer between PCM and fluid: e.g., the use of fins or metal inserts [1]-[2] can improve the thermal conductivity of the system. In this context, the melting and solidification process of the paraffinic PCM RT44HC are studied experimentally. To enhance the PCM low thermal conductivity, a finned- tube heat exchanger was dipped in the paraffin. The total energy exchanged, the heat transfer rate, and the melting and solidification times were calculated by changing the inlet water temperature and the water mass flow rate flowing within the heat exchanger.

2. Experimental set-up

To characterize the latent heat storage system prototype, an experimental set-up has been designed and built. The LTES is made by a commercial finned tube heat exchanger (dimensions: 425×215×40 mm), used in fan-coil terminal units, and characterized by a single row of copper tubes and aluminum fins, inserted in a metallic case. Two set of tests were carried out, filling the case with 1.91 kg of demineralized water and 1.5 kg of the paraffinic PCM RT44HC (Rubitherm GmbH, D) (melting range: 41-44 °C, congealing range 44-40 °C, specific heat capacity: 2 kJ/(kg·K), heat conductivity (both phases): 0.2 W/(m·K), heat storage capacity: 250 ± 7,5% kJ/kg) respectively, to compare the thermal behavior of the two materials. The experimental set-up is shown in Fig. 1, where the position of T-type thermocouples is depicted by black dots. Additional details on the test bench are reported in [3]. The charging process (outlined in Fig. 1a by the red arrows) is carried out by flowing hot water from a thermostatic bath inside the copper tube of the heat exchanger. The process is run until the thermocouple recording the lowest temperature inside the LTES (TC1 in Fig. 1b) reaches the threshold value T_H. The latter is defined as the sum of T_{high} (namely the highest value of the PCM melting range, 44°C) and a certain ΔT, varied during the tests. Similarly, the discharging process (blue arrows in Fig. 1a), which is run immediately after the charging one is ended, takes place flowing cold water from the cold thermostatic bath inside the heat exchanger. A fan-coil is used to further decrease the temperature of water outgoing from the heat exchanger. The process is run until the thermocouple recording the highest temperature inside the LTES (TC1 in Fig. 1b) reaches the threshold value T_C. This is defined as the sum of T_{low} (namely the lowest value of the PCM solidification range, 40 °C) and a certain ΔT, varied during the tests.

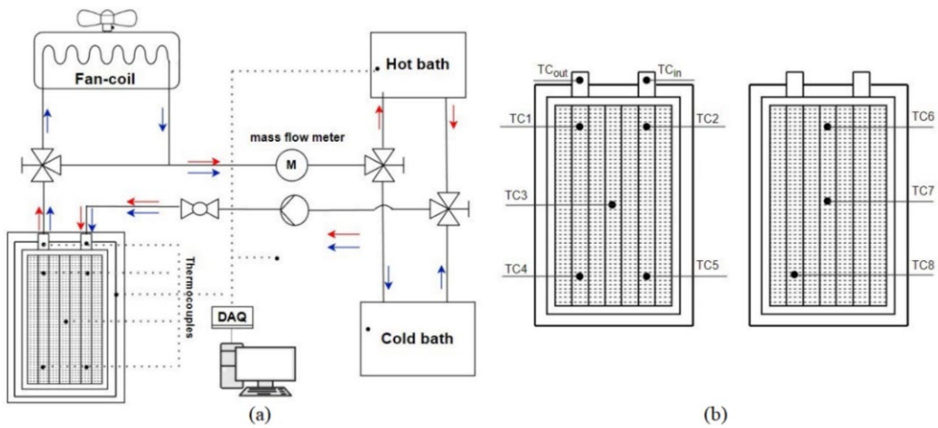

Fig. 1: a) Experimental set-up; b) Position of the thermocouples inside the heat exchanger on front (left) and back sides (right)

To monitor the temperature trend of the PCM during the experimental runs, eight thermocouples are placed within the heat exchanger's fins: five and three sensors are placed on the front and the back side of the heat exchanger, respectively. (see Fig. 1b). Moreover, the inlet and outlet temperature values of water are monitored by two thermocouples.

3. Experimental tests performed and methods

To characterize the innovative LTES, the results obtained using PCM as storing material are compared with those achieved by filling the case with pure water, to quantify the increase of stored thermal energy using PCM instead of water. Several tests were performed for different values of hot and cold inlet water temperature during melting and solidification processes, respectively. Tests with water were performed using one value of temperature difference ΔT equal to 11°C, while two different values of ΔT, equal to 11°C and 26 °C, were used in tests with PCM. In particular, for each case, different values of the water mass flow rate flowing inside the heat exchanger were considered: 25, 50 and 100 kg/h. The energy stored in, or released by, the LTES (E_{TOT}) is defined as the integration of the energy balance on the water side for each sampling time during the test:

$$E_{TOT} = \sum_{t_{start}}^{t_{end}} \dot{m}\, c_p (T_{in} - T_{out}) \Delta t \tag{1}$$

where $\dot{m}$ is the water mass flow rate in the heat exchanger; t_{start} and t_{end} are the time at the beginning and at the end of the test, respectively; c_p is the specific heat capacity of pure water, (T_{in}-T_{out}) is the difference between inlet and outlet water temperature; Δt is the sampling time, equal to 10 s.

3.1. Tests with pure water as storing material

When pure water is considered, the sensible TES was charged and discharged using ΔT = 11°C, considering mass flow rates of the water stream of 25, 50, 100 kg/h. In Table 1, the main results are reported, in terms of energy stored in, or released by, the LTES (E_{TOT}), duration of the charging, or discharging, process (t) and thermal power exchanged (P_{TOT}). Each quantity is characterized by an error band of 9.3 %, calculated by means of the law of propagation of errors.

Table 1: Total energy stored in water, thermal power and duration of the test in charging and discharging processes with ΔT= 11 °C

	Charging process			**Discharging process**		
Water mass flow rate [kg/h]	E_{TOT} ± 9,3% [kJ]	P_{TOT} ± 9,3% [W]	*t* [min]	E_{TOT} ± 9,3% [kJ]	P_{TOT} ± 9,3% [W]	*t* [min]
25	125	286	7.3	116	197	9.8
50	121	484	4.2	111	264	7
100	120	718	2.8	119	385	5.2

The data in Table 1 indicate that the energy given to the system during the charging process is entirely recovered during the discharging process, this behavior also occurs in the other tests.

3.1. Tests with PCM as storing material

Filling the case with PCM as storing material, charging and discharging tests were performed considering two values of *ΔT*: 11 °C and 26 °C. Each process was carried out with the same values of the water mass flow rate of the previous case.

Table 2: Total energy stored in PCM, thermal power and duration of the test in charging and discharging processes with ΔT= 11, 26 °C

		Charging process			**Discharging process**		
ΔT	Water mass flow rate [kg/h]	E_{TOT} ± 9,3% [kJ]	P_{TOT} ± 9,3% [W]	*t* [min]	E_{TOT} ± 9,3% [kJ]	P_{TOT} ± 9,3% [W]	*t* [min]
11°C	25	482	277	29	494	267	30.8
	50	456	495	15.3	458	405	18.8
	100	434	886	8.2	441	605	11.7
26°C	25	485	630	12.8	476	548	14.5
	50	474	1108	7.1	444	957	7.8
	100	458	1790	4.3	423	1525	4.6

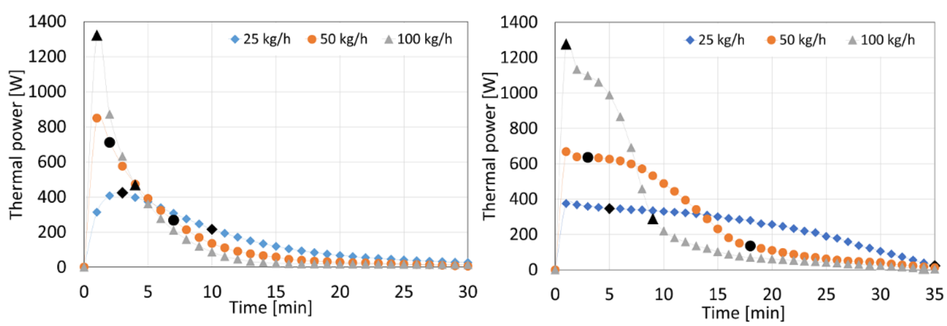

Figure 2: Thermal power trend of the charging process for water (left) and PCM (right) for different water mass flow rates

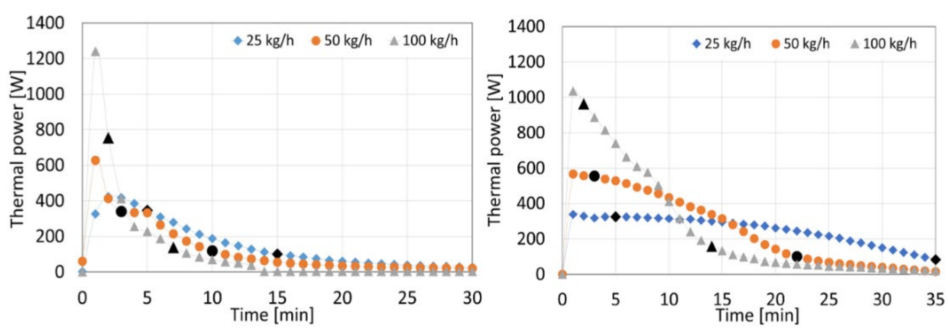

Figure 3: Thermal power trend of the discharging process for water (left) and PCM (right) for different water mass flow rates

Tables 1 and 2 compare the results obtained in terms of energy transferred between water and TES, heat transfer rate and duration of the charging/discharging processes using water and PCM as heat storing material, respectively. The analysis of the experimental measures points out that similar trends occur, with decreasing charging and discharging times as the water flow rate increases. About the charging process, the comparison of Tables 1 and 2 shows how the use of PCM allows to achieve an increase of storing capacity of the LTES of about 300-400% compared to the case of pure water. Unfortunately, a similar increase of charging and discharging times can be observed when ΔT was fixed to 11°C. In this case, due to the lower thermal conductivity of PCM, compared to that of water, both charging and discharging processes were about 3-4 times longer compared to the reference case. Therefore, the heat transfer rate is similar in both configurations. By increasing ΔT, the energy stored by the PCM remains constant, but the charging and discharging times become similar to those obtained with water. As shown in Table 2, the increase of ΔT means a decrease in the PCM charging time of about half, with a consequent increase in the thermal power exchanged during the process. This trend also occurs during the discharging process. Figs. 2 and 3 show the heat transfer rate between the water stream and the TES system as a function of time, during the whole cycle of charge and discharge, using water (on the left) and PCM (on the right) as storing material and employing different water mass flow rates. The bigger markers in the graphs highlight the beginning and the end of each test. The heat transfer rate is not constant along each experimental run and it strongly depends on the water mass flow rate. It is evident that the curves present a decreasing trend, with an initial peak due to the high temperature difference between the heat transfer fluid (water) and the heat storing material during the early stages of the test. Values of these peaks increase with higher flow rates. In addition, it is shown that using water instead of PCM involves curves with higher slopes. This behavior is linked to the fact that water can store only sensible heat, so it shows a rapid temperature variation and, consequently, a fast thermal power decrease, for both charging and discharging tests. On the other hand, using PCM, due to its capacity to store latent heat, it is possible to observe the typical plateau trend linked to the phase change, especially using low flow rates. Therefore, using PCM instead of water allows to have higher values of thermal power for a longer time.

4. Conclusion

In this paper, the thermal storage performance of an innovative LTES system made by a finned tube heat exchanger immersed in a commercial paraffinic PCM is studied experimentally. Storing and thermal performance of the latent storage system were evaluated considering different values of the water mass flow rate and water stream temperature at the heat exchanger inlet, during charging and discharging processes. The LTES results are compared to those of a sensible storage, made by the same heat exchanger immersed in pure water. The results show that the energy stored during the charging phase is completely recoverable in the discharge process, using both water and PCM. The adoption of PCM as heat storage material instead of water allows to increase the storage capacity of the proposed LTES of about 300-400%. On the contrary, charging and discharging times are much longer when PCM is used, due to its lower thermal conductivity and higher storage capacity. Nevertheless, the duration of charging and discharging processes decreases with higher water flow rates and higher temperature differences between inlet water temperature and PCM melting temperature range. In this way, the process can be strongly fastened, allowing a better exploitation of the LTES storage capacity.

Acknowledgements

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