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Latent-Heat Thermal-Energy Storage in Heat Exchanger with Plain and Finned Tube

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Abstract **-** Two design solutions of the heat exchanger containing a material for latent-heat storage are presented. The devices are exposed to controlled energy-charging and -discharging process by virtue of internal water flow. Temperature variations at several monitoring locations are recorded in order to estimate the performance of energy storage and recovery. The experiment confirms that the heat transfer rate in the heat exchanger with fins is significantly larger than in the case of smooth plain tube, which contributes to better storage performance. The unit with plain tube reveals strong temperature gradient in radial direction. In the setup with finned tube, higher temperatures in the storage material as well as shorter charging and discharging times are achieved. Vertical temperature gradient arising during the heating after the phase change indicates development of convective heat transfer in the liquid phase. Melting of the phase-change material, however, turns out to be inhomogeneous yielding remaining solid parts as well as entrapped air bubbles.

Keywords**:** energy storage, heat exchanger, phase-change material (PCM)

1. Introduction

Very frequently, thermal energy, such as obtained from solar or geothermal sources or waste heat released in a variety of technological processes, is not directly used at the place or during the time of its recovery. Its delayed or remote use may be beneficial and can increase efficiency of the considered process. Hence, storage of thermal energy is important for adequate energy management and cost reduction, and supports continual energy supply.

Phase-change materials (PCM) are used to store thermal energy in form of latent heat [1]. They can store relatively large amounts of thermal energy within narrow temperature ranges, which is under some circumstances an advantage over sensible-heat storage. PCM-based energy storage units can be built in form of typical heat exchangers. Beside usual design criteria such as dimensions, shapes, thermal insulation and others, selection of an appropriate PCM-material is also important. It affects if the phase-change temperature matches the required process temperature range, amount of energy to be stored or released, as well as character and rate of heat transfer from heat-transfer fluid (HTF) to PCM and vice versa. Accordingly, storage capacity as well as charging and discharging time are of considerable practical relevance and are remarkable demands in design of energy storage units and phase-change temperature of the adopted material certainly determines applicability of the storage system considered. There is a large variety of materials which can be used for that purpose. Often, materials with solid-liquid phase change are preferred, due to their smaller volume change or smaller pressure change arising in the storage devices.

An important issue in development of PCM-based energy storage systems is low thermal conductivity of PCMs resulting in relatively low heat transfer rates throughout the storage medium. Properly arranged and distributed contact surface between HTF and PCM could offer a solution.

This work is aimed to clarify characteristic phenomena in the behavior of the storage material as well as to identify parameters decisive for appropriate design of thermal-energy storage device. The work is focused on relatively low process temperatures, such as arising in applications for domestic heating or use of solar thermal energy. In the previous works, we used both computational and experimental methods to study behavior of a paraffin-based PCM. We analyzed thermal energy storage in a simple shell-and-tube heat exchanger [2], as well as in a heat exchanger with a coil pipe in order to increase the contact area between the PCM and the HTF [3] [4]. In this study, the main objective is to analyze a design solution for increase of heat transfer rate in a storage device. A new heat exchanger with finned tube is constructed and its performance is compared with that of the corresponding heat exchanger with plain tube. Beside that, applicability of a salt-hydrate-based material with melting temperature higher than that for paraffin-based PCMs is tested and analyzed.

2. Experimental Setup

The thermal-energy storage units built and tested in this study are illustrated in Fig. 1. A copper tube with outer diameter of 18 mm is placed axially in a bottle-like transparent plastic container, whose diameter is 60 mm and the height is 160 mm. The remaining interior of the container is filled with a PCM as the medium for storage of thermal energy. For that, sodium acetate trihydrate is used in this work. At room temperature it is in solid state, in powder form. Its melting starts at the temperature of about 58°C, and becomes transparent liquid about 65°C -75°C.

The device analyzed here is oriented vertically. Water is used as the HTF and flows through the copper tube from the bottom side. Upstream the storage unit, an electric heater with a thermostat is mounted, to keep nearly constant water temperature at desired level. Two processes are observed: (i) charging, when the PCM in the container is in solid state, and water with temperature above the melting temperature of the PCM flows through the copper tube, and (ii) discharging, when the PCM in the container is in liquid state, and water with temperature below the melting temperature of the PCM is used. Thus, energy charging and discharging occurs from the bottom upwards and from the interior outwards.

Two different design variants are tested: a copper tube with plain outer surface, and a copper tube with copper fins mounted on its outer side in order to increase the heat transfer rate into or from the PCM. Outer diameter of the fins amounts to 44 mm, the distance between two neighbouring fins is 10 mm. Reduction of the container volume due to the fins is relatively small and is not regarded as relevant.

Thickness of the thermal insulation layer wrapped around the container is 10 mm.

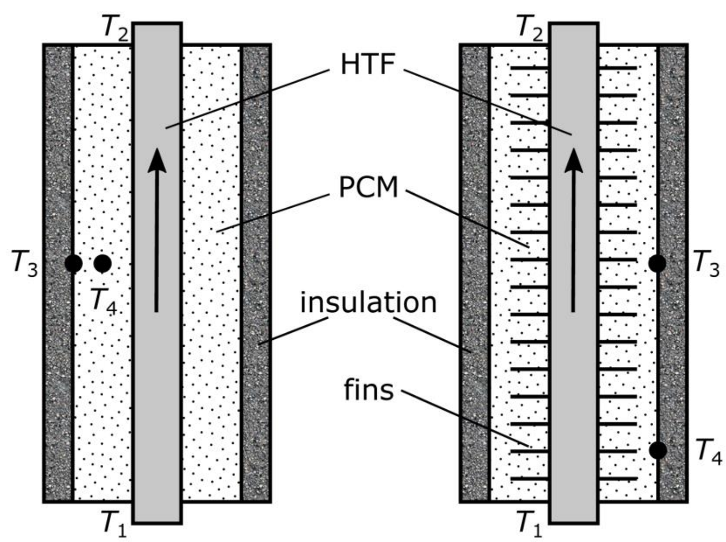

Fig. 1: PCM-filled thermal-energy storage unit with plain pipe (left) and with fins (right). Positions of temperature sensors (T_1-T_4) are indicated.

Temperature variation is measured at four positions (see points T_1 to T_4 in Fig. 1) using type-K thermocouples (Nickel-Chromium/Nickel). Measurement accuracy is 0.1°C. Positions T_1 and T_2 are placed at the inlet and the outlet of the copper tube, where the temperature variation of the HTF is measured in order to estimate energy transferred from the HTF into the storage unit and vice versa. Measurement point T_3 is located at the half of the container height, at its outer surface, but inside the insulation layer. Temperature at this point, depending on its value compared to phase-change temperature of the PCM, is an indicator showing if the phase change in the container is completed.

In the device with the plain copper tube, measurement point T_4 is placed in the PCM, at half of the container height and at the midpoint between the copper tube and the container wall in radial direction. This location allows better observation of the storage material behavior during the heat transfer process. The thermocouple is guided from the top side in order to avoid possible leakage of the storage material, which could arise if the thermocouple would be guided through the container wall. In the device with the finned copper tube, guidance of the thermocouple to a measurement point in PCM from the top side is obstructed by the fins. Hence, it is decided to place measurement point T_4 at the outer container wall, 2 cm from its bottom, in order to follow the heat transfer in vertical direction.

Sampling period of temperature measuring is 10 s.

3. Results

Fig. 2 shows the temperature histories measured for the storage unit with the plain tube (left) and with the finned tube (right), and includes both charging and discharging process. The average water temperature at the inlet is about 80°C during the charging regime, while it is about 40°C in the discharging period. The average flow rate of the HTF is about 0.3 l/min.

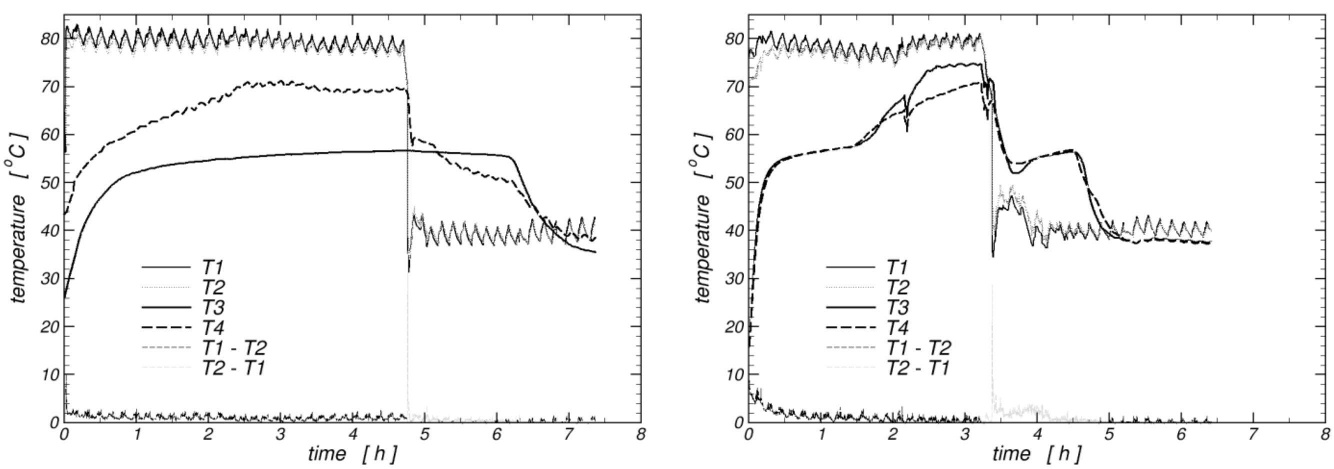

Fig. 2: Measured temperature histories, with smooth plain tube (left) and with finned tube (right).

In the storage unit with plain tube, two obvious effects are observed: (i) considerable temperature gradient in radial direction represented by the temperature difference T3-T4, and (ii) the container-wall temperature (T3) remains below the melting point of the storage material. Both effects are attributed to the low thermal conductivity of the PCM. The interior temperature T4 increases faster than the temperature T3, as expected, and reaches the values above the melting point. Interestingly, different measurements showed that phase change in the interior may, but does not necessarily appear at the nearly constant temperature. In the case shown in Fig. 2, temperature in PCM monotonically increases in the first 2.5 hours, including smooth transition to the liquid phase, after that period a stationary temperature is achieved. The temperature at the container wall (T3) however remains below the melting point for the entire time of testing. After its obvious increase in the first hour, see the corresponding curve in the diagram, the subsequent change in slope reveals that it is affected by the phase-change process in the interior. However, the heat transfer requires considerably longer times, so that the temperature increase near the wall is very slow. The achieved temperature level implies that the storage medium is not completely molten at the outer wall. Visual inspection confirms this, since the outer side of the PCM remains non-transparent for the entire time of the experiment (not shown here).

In measurements with the finned-tube device T3 and T4 represent the container wall temperatures at two different vertical positions, i.e. temperature gradient in vertical direction. In the first two hours of charging their variation is quite similar, implying that the vertical temperature gradients seem to be negligible. The slope of the curve is steeper to some extent than in the case of the plain tube device. Also, realized wall temperatures are significantly larger than in the device with the plain tube. This confirms that the heat transfer rate in the finned arrangement is faster. Further heat supply beyond the phase-change stage, however, results in increase of temperature difference: T3 temperature is higher than T4. This is addressed to convective heat transfer in the liquid phase. Note that the sudden drop in T3 and T4 temperature variation after two hours is caused by temporary removal of insulation in order to make photographs. After the insulation layer is returned in original place, the wall temperature is quickly recovered.

T1 and T2 variations in both design variants exhibiting an obvious zig-zag pattern result from the thermostat action in the electric heater. This is also partly seen in the temperature histories in the interior of the PCM (T4 in the plain-tube unit, figure left), as well as at the container wall (T3 in the finned-tube unit, figure right). It is assumed that these temperature variations are transferred by convection in the liquid phase, since they are not observed at the PCM temperatures around the melting point or in solid state, when heat conduction dominates.

Temperature increase in the HTF during the discharge process (gray line representing the difference T1-T2) in the device with the fins is clearly larger than in the device with the plain tube, since more energy was stored previously in the form of latent heat.

Sub-cooling is an effect typical for salt hydrates, such as the material used here, and it is evident in the cooling curve of the storage unit with the fins (Fig. 2 right). The recorded container-wall temperatures T3 and T4 follow the temperature variations inside the container with a slight difference due to its thermal resistance. They drop below the melting point and later temperature increase up to the level slightly below the melting point of 58°C is clearly seen. Although not distinctly recognized in the recorded results, sub-cooling is also present in the storage unit with the plain tube. Here, however, the heat released during the crystallization seems to be smaller than the heat removed from the PCM (by the HTF or by the losses into the environment), hence practically no temperature increase is recorded and plateau typical for phase-change process is not observed. Similarly, plateau effect is not seen in the charging regime.

Finally, in both devices the discharging regime is stopped after the PCM temperature falls below the HTF temperature, which indicates that the heat gained from the HTF is less than the heat released to the environment.

Figure 3 shows the storage unit during the charging regime. The storage medium is in solid state at room temperature and it is non-transparent before the heating (left). After melting stage is stopped, three different regions in the PCM are distinguished: (i) the transparent region in the largest part of the storage unit representing the molten PCM, (ii) the bottom region where the PCM remains non-transparent and its melting is not completed, and (iii) the top region where air bubbles released during the melting are agglomerated. A part of the air bubbles remains stuck to the container wall, while the other part is entrapped beneath the fins (right). Entrapped air bubbles remain inside the PCM during the solidification, making it porous and degrading herewith its thermal conductivity.

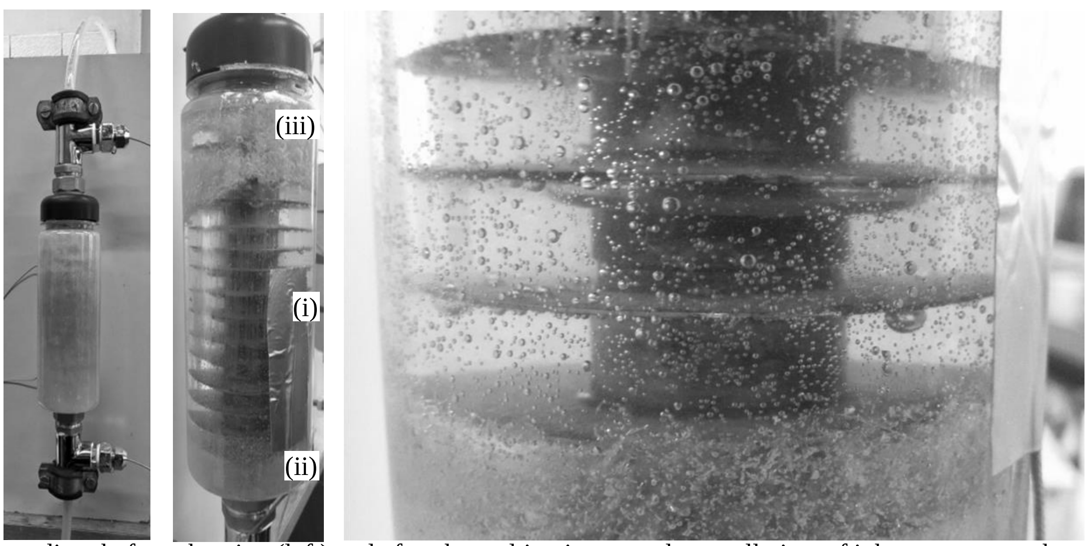

Fig. 3: Storage medium before charging (left) and after the melting is stopped: overall view of inhomogeneous phase change (middle), and magnified view of entrapped air bubbles (right).

4. Conclusion

The heat exchanger with fins provides considerably faster heat transfer, and herewith shorter charging and discharging times, than the exchanger with the plain tube. Also, higher temperatures are achieved in the entire storage material. On the other side, the fins obstruct the vertical upward flow of the air bubbles released during the melting of the PCM. We assume that the entrapped air bubbles make the heat transfer in the PCM slower to some extent.

Melting at the bottom of the unit is not completed. Additional insulation of the copper tube outside the container and the attached fittings is needed.

The results can be used as a reference for computational simulation of the phase-change process. Future work will be focused on optimisation of the storage unit based both on experimental and computational analysis.

Acknowledgements

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