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# Performance analysis of industrial PCM heat storage lab prototype

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ABSTRACT

A 140 l lab scale shell-and-tube PCM heat storage was built and tested, and the experimental results were compared to a numerical model. Natural convection in the PCM was found to significantly influence the local temperature distribution in the storage vessel, which could not be predicted well by the model, since the model assumes only conductive heat transport in the PCM. Nevertheless, the overall thermal power output of the storage could be predicted fairly well, if a correction term was used in the model to compensate for the enhanced heat transfer in the molten PCM. Experimentally, a horizontal orientation was found to be beneficial due to increased heat exchange during charging (melting). Comparing the two PCMs used in the testing (RT70 and $MgCl_2{\cdot}6H_2O$), it was found that the RT70 had stable performance while the salt hydrate showed a reduced melting enthalpy which was ascribed to phase separation. For the RT70, a thermal power of 5 kW is obtained during phase change in the charging phase, and 3.5–2 kW during phase change in the discharging phase, while for $MgCl_2{\cdot}6H_2O$ this was 3.5 kW and 3–2 kW respectively.

## 1. Introduction

Heat storage can be applied to increase industrial energy efficiency and reduce installation costs, by providing peak heating demand, by storing intermittent waste heat for later use and by decoupling of thermal and electrical yield of CHP systems. Phase change materials have the advantage of a large energy storage density in a small temperature range around the melting point. However, the effective performance is often limited by the low thermal conductivity of the PCM. Therefore, much effort has gone into enhancing effective PCM conductivity [1,6], or optimizing the thermal design geometry for PCM storages [2]. Important for the latter is also the large effect that natural convection in molten PCM can have in the melting phase [5,3], enhancing charging power.

In the Dutch project “LOCOSTO”, the feasibility of high temperature Phase Change Material (PCM) heat storage is investigated for storage of industrial waste heat in the temperature range between 70 °C and 200 °C. The focus is on stationary PCM heat storage applications on industrial sites, focusing on heat storage combined with CHP, recuperation and re-use of waste heat from batch processes and emergency backup heating. An effort was made to develop a prototype representative of a typical industrial system, to investigate the effective power, temperature distribution and optimal orientation of the storage as realistic as possible. In addition, detailed measurements on the temperature distribution in the storage were carried out, to assess the match between model and experiments.

Industrial heat storage systems are typically designed for high power, high energy content, high reliability and high temperature, setting specific requirements for PCM materials and PCM additives. In addition, economic return times should be short, which is the more stringent since industrial energy prices are relatively low. Therefore, as much as possible, use is made of low cost and proven industrial components in the upscaling from labscale prototypes to industrially relevant scale, as well as relatively low cost PCM materials. The thermal design was realized in a cooperation between ECN and Bronswerk Heat Transfer. The PCM storage design is based on a shell and tube heat exchanger, being an industrial standard solution, in which the shell side is filled with the PCM. This introduces a number of design parameters, such as pitch and number of tubes, depending on the effective conductivity of the PCM.

## 2. Modelling heat transfer

A model has been developed in matlab, to calculate the thermal power of a shell-and-tube geometry, for a shell filled with PCM and the tubes carrying the heat transfer fluid. The model is suitable of calculating the time dependent thermal power and state of phase for different amounts of tubes, tube pitches and tube lengths. The matlab

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**Nomenclature**

| | |
|---|---|
| ΔH | Melting enthalpy PCM (J/kg) |
| ΔT | Temperature difference (°C) |
| ρ | Density PCM (kg/m$^3$) |
| λ | Conductivity PCM (W/m K) |
| R | Radius of tube (m) |
| L | Length of tube (m) |
| s | Distance of progression of the melting front (m) |
| t | Time (s) |

model is based on the following assumptions:

1. In the PCM, only conductive heat transfer is calculated. Convection in the molten PCM is not explicitly calculated, but corrected for by assuming a higher effective heat exchange between adjacent numerical grid cells containing PCM in liquid state (as will be elaborated later in Fig. 13).
2. The calculation focuses on a representative segment of the shell-and-tube geometry (typically a quarter of a tube, see Fig. 1). Because of this choice, the effect of heat loss from the surface of the tank to the ambient is not taken into account. In addition, this choice implies that the model assumes a 90° (¼-tube) rotational symmetry, disregarding any local asymmetry that would result from natural convection (because of the direction of the gravitational force). The boundary condition over the symmetry plane between tubes (blue line in Fig. 1b) is set by assuming inversely symmetric boundary conditions ($T_{1,y} = T_{x,y}, T_{2,y} = T_{x-1,y}$, etc.). In the calculations, usually a grid of radial × axial × tangential = 10 × 10 × 10 cells was used.
3. Heat transfer in the PCM is only in the radial direction. Only via the heating up of the tube flow, the longitudinal direction is taken into account. Heat transfer between tangentially connected cells is ignored, which is of some importance as the radial direction changes in length, making the system asymmetric in the tangential direction, as seen in Fig. 1b.

In order to validate the model, a comparison was made with an analytical solution for a single tube with PCM at the outside (without the presence of adjacent tubes). According to Mehling and Cabeza [4], the analytical solution for this case is:

$$t = \frac{\rho\Delta H}{2\lambda\Delta T}s^2 \times \left(\left(1+\frac{R}{s}\right)^2 \ln\left(1+\frac{s}{R}\right) - \left(\frac{1}{2}+\frac{R}{s}\right)\right) \tag{1}$$

Here, ΔT is the difference between the tube temperature and the melting temperature of the PCM (°C). Note that this equation takes into account only the melting heat; the sensible heat (which is relatively small for a small temperature range) is ignored.

From this equation, the power can be determined analytically according to

$$q = \rho\Delta H\frac{ds}{dt} \times 2\pi(R+s)L \tag{2}$$

Fig. 2 shows a comparison of the storage power calculated by the analytical solution and by the numerical Matlab model, for the case of a high flow rate (keeping the temperature in the tube effectively constant in the flow direction). As can be seen, for the case of large pitch (Fig. 2a) and also initially for the case of small pitch (Fig. 2b), the results from the analytical solution and the model are almost identical, as expected. However, for small pitch after 1000 s (Fig. 2b), the solidification fronts of the adjacent tubes start to overlap. This reduces the power that can be extracted according the Matlab model (taking into account the effect of adjacent tubes) compared to the analytical model (that assumes only one tube without adjacent tubes). This clearly shows the added value of the present Matlab model compared to the analytical model for simulation of the PCM storage.

Also, the model performance was compared qualitatively to the results found in a small lab prototype PCM storage. This lab prototype was built based on a shell-and-tube configuration with 5 tubes, as shown in Fig. 3. Geometry-induced inhomogeneities and differences in solidification of organic PCM and salt hydrates were observed; in particular, significant crystallization needles were seen for the salt hydrate. The comparison with the model is shown in Fig. 4, indicating a fairly good correspondence between lab prototype and model. However, it can also be observed that the melt in the experiment is not axisymmetric; already in Fig. 3b, it can be observed that the molten area above the middle tube is significantly larger than the molten area below this tube. This indicates that in the charging phase, natural convection in the PCM increases the melting rate. Note that such asymmetry around the tube cannot be captured by the present Matlab model, which simulates only an individual ¼-tube (under the effect of symmetric boundary conditions simulating the effect of the adjacent tubes).

## 3. Large scale lab prototype

Next, a large scale lab prototype was built with an internal shell volume of 142 liters to be filled with PCM. The heat exchanger is shown in Fig. 5. It contains 49 U-tubes for heat transfer, with an outside diameter of 12 mm and a triangular pitch of 36 mm. The full prototype is shown in Fig. 6. The design allows the vessel to be placed in either horizontal or vertical position, to investigate the effect of vessel orientation on thermal performance of the PCM (related to the direction of natural convection in the molten PCM). The vessel was connected to a heating/cooling infrastructure, as shown in Fig. 6. The inflow temperature to the vessel was controlled by a thermostatic bath, with sufficient cooling/heating power to have an inlet temperature stable within 0.5 K of the setpoint value.

Two different types of PCM materials have been tested in the vessel; Rubitherm paraffin PCM RT70 (an organic PCM with a melting temperature of 70 °C) and pure $MgCl_2{\cdot}6H_2O$ (a salt hydrate PCM with a melting temperature of 117 °C). In horizontal orientation, the prototype could be filled with 103 kg of Rubitherm paraffin PCM RT70 (in vertical orientation, a slightly lower PCM content of 85 kg was realized, due to limitations caused by the position of the filling valve).

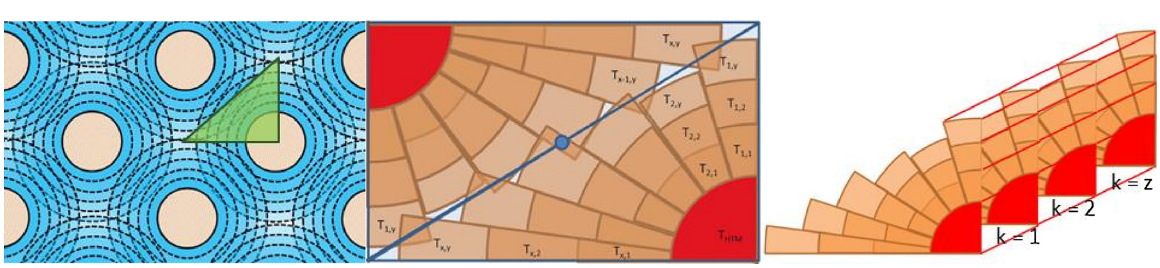


**Fig. 1.** Grid layout of shell-and-tube matlab model. (a) Overall heat exchanger geometry, (b) Boundary conditions for quarter tube calculation domain, (c) longitudinal direction.