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Experimental set up for the investigation of partial phase changes of phase change materials

Martin Zálešák[1]*, *Patrik* Bouchal[1], *Milan* Ostrý[2], and *Jiří* Hejčík[1]

[1]Brno University of Technology, Faculty of Mechanical Engeneering, Energy Institute, Technická 2896/2, 61669 Brno, Czech Republic

[2]Brno University of Technology, Faculty of Civil Engeneering, Institute of Building Structures, Veveří 331/95, 60200 Brno, Czech Republic

Abstract. Thermal energy storage with phase change materials (PCMs) has attracted a lot of attention in the last several decades. Most PCMs do not change phase at a constant temperature but rather in a certain temperature range. It means that the PCM need to transit through its phase change temperature range to fully change phase from the solid state to the liquid state and vice-versa. The situation, in which the phase transition begins and/or ends within the phase change temperature range (in the mushy zone), is usually called a partial phase transition (or a partial phase change). The partial phase transitions occur quite often in real-life thermal energy storage systems with PCMs; especially when a PCM has a wide phase change temperature range. The behavior of PCMs during the partial phase transitions is poorly understood at the moment, because the experimental techniques used for the characterization of PCMs (such as the differential scanning calorimetry – DSC) are difficult to apply for the study of partial phase transitions. The lack of knowledge in this area influences the accuracy of phase change simulation models. The main goal of the experimental investigations, described in the paper, was to obtain data for the development of a simulation model for partial phase changes. The experimental set up for the investigation of partial phase changes of PCMs has been proposed, assembled, and the pilot measurements have been conducted. The experimental set up consists of two water storage tanks (that can be maintained at different water temperatures), a water-PCM concentric tube type heat exchanger and a data acquisition system. The water flows through the central tube of the heat exchanger while the PCM is located in the annular space of the exchanger. The water storage tanks, maintained at the temperatures within the phase change temperature range of a PCM, allow for the investigations of the heat storage cycles consisting of partial phase changes.

1 Introduction

In last several decades, there has been an increasing interest in the thermal energy storage systems integrating phase change materials (PCMs). Thermal energy storage plays an essential role in mitigating the delay between energy supply and demand in many different applications [1]. Since the PCMs are the central part of such systems, the knowledge of their thermophysical properties and thermal behaviour is necessary for the successful numerical analysis. As has been shown by many authors in recent years, some PCMs exhibit an asymmetrical behaviour during the phase transition, often referred to as the thermal hysteresis [2, 3].

Since the most of PCMs undergo the phase transition in a temperature range rather than at a constant temperature, we can differentiate between 2 scenarios [4] which are illustrated in Figure 1. The direct phase transition between solid and liquid states, which begins and ends outside the "mushy" zone is called the complete phase change. Similarly, the situation in which the phase transition begins and/or ends within the "mushy" zone is usually called the partial phase change. The thermal behaviour during the partial phase change is not very well understood at the moment, which lowers the overall accuracy of numerical model of heat transfer in PCMs [5]. The differential scanning calorimetry (DSC) and temperature history (T-history) methods are used quite commonly as experimental methods for the determination of the enthalpy of fusion and its temperature dependency, however the results are usually very difficult to apply considering the partial phase change [2].

Many authors were investigating the partial phase change lately. Thonon et al. [6] conducted a study investigating the phase change hysteresis and supercooling numerically and experimentally. The authors presented the analytical model of the thermal behaviour of a PCM experiencing the partial phase change cycles. Various heating/cooling rates were considered in the study. The experimental validation was carried out on a PCM brick sample, measuring the heat flux and the PCM temperature. The studied material was PEG6000 which is a polymer PCM suitable for domestic hot water storage. The authors reported a good agreement between experimental and simulated results considering the complete phase change. The

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[*] Corresponding author: 162098@vutbr.cz

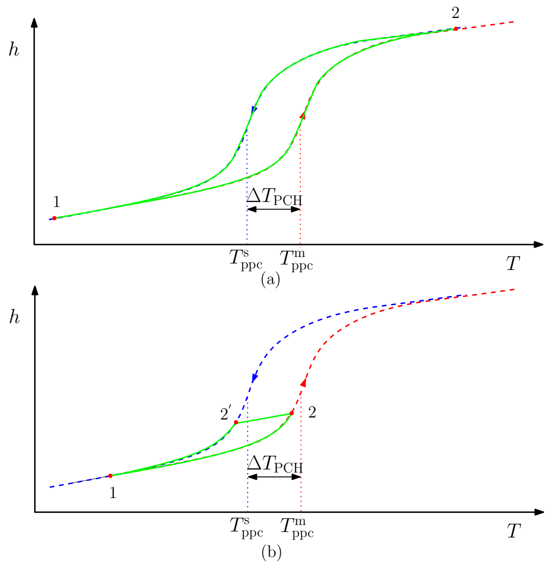

Fig. 1. The h-T dependency during a (a) complete phase change and (b) partial phase change.

numerical modelling of the partial phase change was also shown to be satisfactory, however there were some discrepancies in the thermal behaviour of the cooling process (after partial melting of PCM). Barz [7] experimentally and numerically studied the phase transition behaviour of three commercial paraffin-based PCMs in a plate-fin heat exchanger. The heat exchanger was subjected to series of cyclic heating/cooling cycles within the phase temperature range. The results have shown that the performance of the "curve scale" phase change hysteresis model developed by the authors was superior in comparison with a model based on the phase fraction-temperature curve of the heating curve only. The three phenomenological models for prediction of temperature-induced phase transitions were proposed by Barz et al. [8] - the "curve track", the "curve switch" and the "curve scale" models. The proposed models are directly identified from the data from complete melting and solidification, which reduces the effort for model calibration (eg. manufacturer material properties can be used). The predictive performance of the novel "curve scale" model during 26 partial load cycles has shown to be superior compared with the "curve switch" and the "curve track".

As has been shown in the literature, the behaviour of PCMs undergoing the partial phase change is still not well understood with a very little experimental validation conducted. The experimental methods for the determination of the thermal properties (such as DSC or T-history) have proven to be very difficult to implement for this purpose (considering partial phase change) since they are limited by the sample size (usually only up to 10 mg) and the results significantly depend on the heating/cooling rate. As an alternative, many authors combine the numerical model of the thermal system containing a PCM with experimental investigations of such a system, creating the inverse identification problem. When coupled with a suitable optimization method and well defined initial and boundary conditions, the inverse problem could be solved providing the information about the thermal behaviour of a selected PCM undergoing a partial phase transition. The authors of this study have already investigated a similar inverse identification procedure focusing on a complete phase change, showing promising results [9].

2 Experimental setup

The experimental setup has been constructed, consisting of two separate water storage tanks (which are maintained at different temperatures) connected to a water-PCM concentric tube type heat exchanger with the data acquisition system as is shown in Figure 2. The inlet water temperature of the water-PCM heat exchanger can be controlled by 3-way valve (combining water from the hot and cold water storage tanks). The Pt100 temperature probes were used for the measurement of inlet and outlet water temperatures. The mass flow of water was measured after the water-PCM heat exchanger and in the end the water flow did lead into drain. The water flows though the central tube of the heat exchanger. The studied material was paraffin-based PCM Rubitherm RT 35 HC which was located inside the annular space of the concentric tube heat exchanger with total mass of the PCM equal to 0.98 kg. The material properties of the RT 35 HC are summarised in the Table 1.

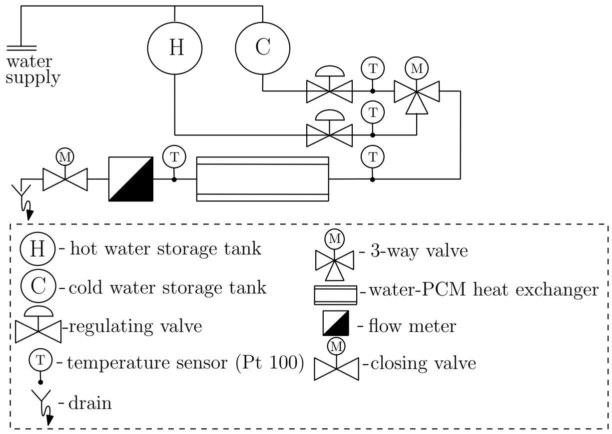

Fig. 2. Schematics of the experimental setup.

3 Methods

The proposed procedure for the inverse identification of the thermophysical properties of a PCM consists of four main parts:

1. Numerical model of the studied thermal system
2. Parametrization of the material properties which describe the thermal behaviour
3. Experimentally measured temperatures in specific locations
4. Suitable optimization method.

Table 1. Rubitherm RT 35 HC manufacturer properties

Material property	**Value**	**Unit**
Phase change temperature	35	[°C]
Heat storage capacity*	240	$[\mathrm{kJ\,kg^{-1}}]$
Specific heat capacity	2000	$[\mathrm{J\,kg^{-1}\,K^{-1}}]$
Density	800	$[\mathrm{kg\,m^{-3}}]$
Heat conductivity	0.2	$[\mathrm{W\,m^{-1}\,K^{-1}}]$

*(latent and sensible heat between 27 - 42°C)

The numerical model is based on 2-D heat conduction inside the PCM with governing equation:

$$\rho c_{\mathrm{eff}}(T)\frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right), \qquad (1)$$

where T is temperature, τ is time, k describes thermal conductivity, ρ is density and x, y are spatial coordinates. The phase change is modelled using the effective heat capacity method, which uses the specific heat capacity and transforms it into the function of temperature $c_{\mathrm{eff}}(T)$. The shape of such function was defined in form of a Gaussian function as:

$$c_{\mathrm{eff}}(T) = c + c_{\mathrm{L}_f}\exp\left\{-\frac{(T - T_{\mathrm{ppc}})^2}{\sigma}\right\}, \qquad (2)$$

with c being specific heat capacity, c_{L_f} is height coefficient, T_{ppc} is peak phase change temperature and σ defines the sharpness of the Gaussian function.

The proposed study is dealing mainly with the overall inverse identification procedure, the experimental set up construction and experimental data acquisition and preparation. As can be seen in the Figure 3, the interrupted melting process could be modelled either by using the effective heat capacity method or enthalpy method. The melting process is interrupted at specific temperature T_{sw} and reversed to solidification with chosen transition method being proposed by Bony and Citherlet in [10] also very often referred to as the "curve switch" model [7, 8].

Parameters of curves following the behaviour in Figure 3 are all combined into the parameter vector $\mathbf{p}$. The direct evaluation of the numerical model (considering specific set of model parameters) leads to a specific outlet water temperature $T^{\mathrm{water}}_{\mathrm{out,sim}}$. The objective function was defined as a sum of squared differences between the experimentally measured and simulated outlet water temperatures:

$$\mathtt{OF}(\mathbf{p}) = \sum_{p=0}^{\frac{t_{\max}}{\Delta t}} \left(T^{\mathrm{water}}_{\mathrm{out,sim}} - T^{\mathrm{water}}_{\mathrm{out,exp}}\right)^2. \qquad (3)$$

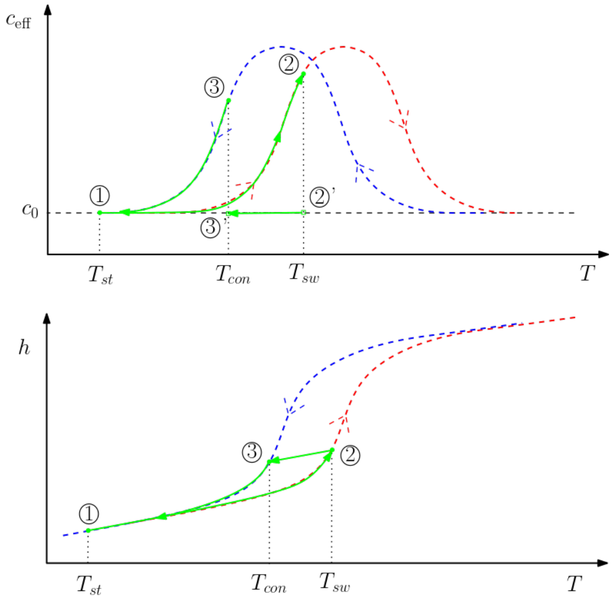

Fig. 3. Parametrization of the interrupted melting process using c_{eff} –T and h–T dependency, according to Bony and Citherlet [10].

Combined with the experimentally measured outlet water temperature $T^{\mathrm{water}}_{\mathrm{out,exp}}$, the objective function is then iteratively evaluated following a suitable heuristic optimization method such as: particle swarm optimization (PSO) method, differential evolution (DE) method or genetic algorithm (GA) until the termination criterion is fulfilled and the vector of optimal parameters $\mathbf{p}_{\mathrm{OPT}}$ is determined.

4 Results

When the experimental setup for the investigation of partial phase changes was assembled the pilot experiments were conducted and the obtained data were evaluated. As can be seen in the Figure 4 and 5, the inlet and outlet water temperatures were measured for several different heating and cooling cycles. During the heating phases, the temperature of 55 °C was set in the water-PCM heat exchanger inlet, utilising only water from the hot water storage tank. Main goal of the first scenario was to fully undergo the phase transition of the PCM, which could be used for the description of thermal behaviour during complete phase change. After about 40 minutes, the PCM in the annular cavity was considered fully molten and the process was reversed, discharging the heat from the heat exchanger with the cold water with temperature of 21 °C until the whole PCM was completely solid again.

In order to investigate the thermal behaviour of PCM during the partial phase change, in total 5 different melting/solidification cycles were measured. The individual scenarios did differ in the charging/discharging time being 1, 2, 3, 5 and 10 minutes.

5 Conclusion

The main outcomes of the presented study can be summarised as:

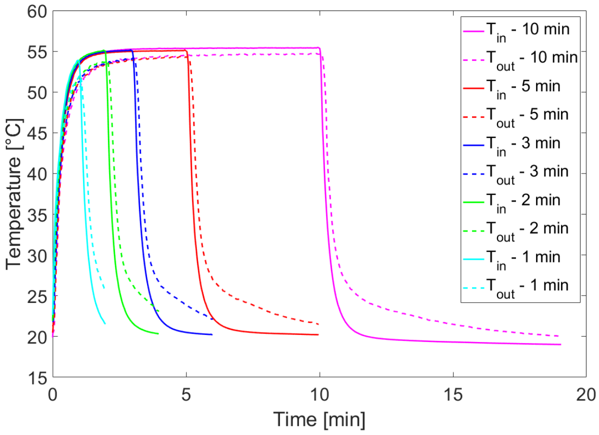

Fig. 4. Inlet and outlet water temperature for different charg-ing/discharging time intervals.

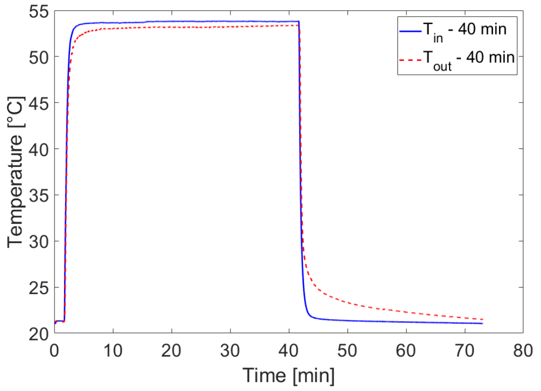

Fig. 5. Inlet and outlet water temperature for complete phase transition

- The experimental set up with the water-PCM heat exchanger was designed and constructed.
- The initial measurements were conducted, starting with the complete phase transition heating/cooling cycle. However, since the objective of the inverse identification procedure is to determine the thermal behaviour of PCM during the partial phase changes, inlet/outlet water temperatures of water-PCM heat exchanger were measured for a series of interrupted (incomplete) heating cycles.
- The inverse identification procedure was proposed and possible parametrization of the effective heat capacity curve was suggested. In the future studies, the inverse problem will be defined (with use of the experimental data measured in this study) and solved using a suitable optimization method (eg. PSO, DE, GA).

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