# Experimental and numerical investigation of a phase change energy storage system



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# Experimental and numerical investigation of a phase change energy storage system

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**Abstract**. Latent heat storage systems are an effective way of storing thermal energy. Recently, phase change materials were considered also in the thermal control of compact electronic devices. In the present work a numerical and experimental investigation is presented for a solid-liquid phase change process dominated by heat conduction. In the experimental arrangement a plane slab of PCM is heated from above with an on-off thermal power simulating the behaviour of an electronic device. A two-dimensional finite volume code is used for the solution of the corresponding mathematical model. The comparison between numerical predictions and experimental data shows a good agreement. Finally, in order to characterize this thermal energy storage system, the time distribution of latent and sensible heat is analyzed.

## 1. Introduction

Heat storage systems using phase change materials (PCMs in the following) are an effective way of storing thermal energy due to the high energy storage density and the isothermal nature of the storage process. Latent heat storage systems have been widely used in building envelopes, residential heating and cooling, solar engineering, and spacecraft thermal control applications [1]. In recent years the utilization of PCMs has been also considered in the thermal control of compact electronic devices.

The heat generated by an electronic circuitry must be dissipated to prevent immediate failure and assure long term reliability. For high specific power and/or compactness, the limited capability of the traditional air cooling techniques requires the use of new technologies. In this area PCM based cooling is a very attractive technique of thermal control, considering the advantages of the PCMs such as: high specific heat, high latent heat, small volume change during phase change, availability of PCMs at convenient melting temperatures, non-toxicity, inertness and non-corrosiveness. A PCM energy storage system can be useful also to delay the heat release so to reduce the need of heat transfer surface, in particular for situations where the heat dissipation is of periodic nature or a sudden transient.

As the base case of thermal control unit (TCU in the following), a layer of PCM encapsulated in a hermetically sealed container can be considered. Referring to this solution, Alawadhi and Amon [2] investigated the thermal energy management issues associated with portable electronic equipment. The performance of a PCM based TCU was analysed for both constant and variable power operations. Tan and Tso [3], experimentally studied the cooling of a mobile electronic device using a PCM based TCU inside the device. They observed that the effectiveness of the TCU depends on the amount of PCM

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used, as expected. Kandasamy *et al.* [4], investigated experimentally the effect of orientation of PCM based heat sinks and concluded that orientation has a limited effect on the thermal performance.

In applications [2-4] the low thermal conductivity of the PCMs made the charging and discharging slow during phase transitions. Different solutions were then developed to enhance the heat transfer in these PCM based TCUs, all related to the insertion of conducting paths or materials in the heat storage volume: discrete elements such as pins and fins, metal matrices or foams, nano and micro sized metal and metal oxide fillers, carbon nano tubes or fibers, graphite, exfoliated graphite or graphene [5,6]. Such a solution is referred to as a thermal conductivity enhancer (TCE in the following).

Limiting the analysis to TCUs where fins of different geometry are inserted in the PCM layer, Lamberg et al. [7] studied a system designed to store thermal energy when peaks of temperature are encountered in the operating conditions of a portable electronic device. Kandasamy *et al.* [8] analyzed experimentally and numerically the performance of a finned heat sink, where the throats were filled with a PCM. This energy storage system showed its potential as TCU in the transient electronic cooling applications. Wang *et al.* [9] carried out a parametric study on the performance of a finned heat sink filled with PCM. The parameters considered in the analysis were the aspect ratio, the filling of PCM, the level of under-cooling at the boundary. Fok *et al.* [10] focused the analysis on a finned heat sink filled of PCM for portable electronic devices. They concluded that this solution can increase the heat transfer rate during the charging stage, but did not seem to have any significant effect during the discharging stage. Baby and Balaji [11] investigated experimentally the performance of a finned TCE for the thermal management of portable electronic devices. Two different fins were compared. The experiments were carried for constant power dissipation. The time of melting and the final temperature were compared.

Finned surfaces partially filled with PCM, called hybrid systems, are somewhat more difficult to realize. However, these solutions show a lower thermal resistance than the finned TCUs. Gauché and Xu [12] analyzed numerically these hybrid PCM heat sinks providing evidence to the benefits, like a reduced size and the prevention of reliability issues. Krishnan *et al.* [13] investigated the ability of a hybrid PCM heat sink to operate continuously under time-varying cooling conditions. Stupar et al. [14] presented a hybrid PCM heat sink for temperature control of an electronic device. This was obtained by means of the combined action of a fan and a PCM-based energy storage system during peaks of power.

These last applications which combine both passive (PCM) and active (fins and fans) cooling solutions, seem to be of interest in high power amplifiers characterized by different levels of power dissipation. This is the case of the telecom base station power amplifiers, where the power is proportional to the traffic load.

In the present work some preliminary results of a numerical and experimental investigation are presented. The final goal of the research is the development of a hybrid PCM heat sink for power electronics applications, consisting of a parallel plate heat sink with part of the fins immersed in a suitable PCM. As a first step, a TCU consisting of a plane slab of PCM is analyzed for an on/off heating condition. For an easy confinement of the liquid phase, the cylinder geometry is chosen. For this energy storage system in a previous paper we analyzed the solid-liquid phase change process [15] for a constant heating. A two-dimensional finite volume code, validated for comparison with experimental data, was used for the solution of the corresponding mathematical model. In [16] we analyzed the solid-liquid phase change process for a sinusoidal heating. The study provided useful information for some applications, as the improvement of the thermal inertia of building walls.

The available experimental equipment [15-16] is now used to investigate the behaviour of a TCU subjected to an on/off heating. In the experiments, the power and the heat transfer surface are comparable to that of a telecom power amplifier. The specimen is placed horizontally and the heat flows from the top to the bottom. The on/off heating periods are equal. Energy parameters, as the amount of melting during the tests and the min/max temperature difference, are discussed. At this step of the research the phase change process is considered to be dominated by heat conduction. Finally, the time distribution of latent and sensible heat is analyzed.

## 2. Experimental equipment and test procedure

The experimental equipment is described in full details in [15-16]; here just a short description is given. A schematic diagram of the equipment is shown in figure 1. The test cell consists of a hollow cylinder of polycarbonate (150 mm o.d., 140 mm i.d. and 210 mm height). A refrigeration system keeps this base at a temperature lower than the melting point of the test material. The uniform contact between the base and the cooler is enhanced by a thin layer of thermal grease. To reach easily this low temperature during the experiment, the cooling system uses Peltier cells. A uniform distribution of temperature over the whole surface of the bottom wall is obtained by means of nine thermoelectric modules (40 x 40 x 4 mm each). They are sandwiched between two square aluminium plates, 2 mm thick. One of these is finned (fins 40 mm high). The contact between the Peltier cells and the two aluminium plates is again enhanced by thin layers of thermal grease. To improve the heat release by the thermoelectric cooler, the fins are immersed in a constant temperature bath where the water is continuously stirred. The thermoelectric modules are supplied by DC power.

To reduce the heat transfer to the environment, the wall of the cylinder is insulated with a thick layer of expanded polystyrene foam (mean thickness 100 mm).

The test volume (height 51.1 mm) is closed on the top by the heater. The heat flow is obtained by dissipating via the Joule effect an assigned power in a resistor (450 W of nominal power at 220 V). Such a resistor is placed inside a copper disk soldered at the end of a copper pipe (135 mm o.d., 133 mm i.d. and 112 mm height). This copper pipe is placed coaxially inside the polycarbonate container. The gap between the two pipes is used as an auxiliary volume of expansion.

The temperature inside the specimen is measured by copper–constantan thermocouples at different heights. The positions of the thermocouples are shown in Table 1. The first and last thermocouples are in contact, respectively, with the cold and hot walls. The hot junctions of the thermocouples are supported by polycarbonate stands. These prismatic supports (3 mm of side width) guarantee the positions of the thermocouples and avoid the dragging of the solid during the freezing. The wires leave the rigid supports through holes and grooves machined in the bottom wall of the test cell.

A digital multimeter Agilent 3458A is used to measure the electromotive force for each thermocouple. The scanning of the thermocouples during the acquisition is carried out via a switch control unit Agilent 3488A. The data acquisition system is managed through a personal computer by means of an IEEE488 standard interface. The reference joint of the thermocouples is connected to an ice-point reference KAYE model K170. The time is measured with the inner clock of the personal computer.

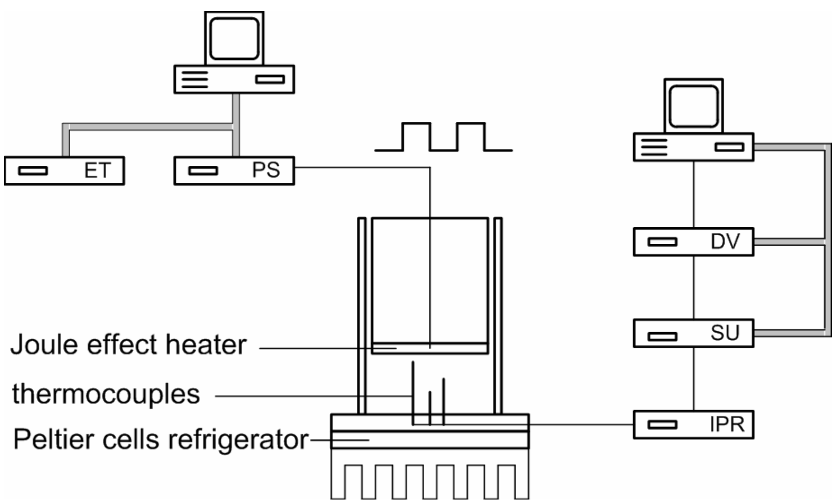


**Figure 1 -** Schematic diagram of the experimental equipment: ET, external trigger; PS, power supply; IPR, ice point reference; SU, switch control unit; DV, digital voltmeter.

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**Table 1 -** Positions of the thermocouples (The origin is placed on the bottom of the specimen).

| TC no. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| z (mm) | 0 | 6.2 | 16.2 | 25.4 | 30.3 | 36.7 | 44.6 | 51.1 |

The measured e.m.f. is converted into temperature by using a third degree polynomial, the interpolation coefficients being computed on the basis of the ASTM temperature–e.m.f. tables for standardized thermocouples [17].

The PCM test material used in the experiments is 99% pure n-octadecane($C_{18}H_{38}$), because it is non-corrosive and non-toxic, chemically inert and stable, with low vapour pressure, small volume changes during melting and large enthalpy release during the phase transition. The n-octadecane does not undergo any hysteresis cycle and its density decreases regularly as the temperature increases. Furthermore, its thermophysical properties, listed in table 2, are well known from the literature [18]. As can be seen, all the thermophysical properties except the density are considered constant with temperature and phase dependent.

While in [16] the heating was constant and in [15] sinusoidal in time, in this set of experiments we heated the sample with an on-off power. This power is obtained by varying the voltage via a power supply Agilent 6032A.

The uncertainty of the data gathered is estimated at the 95% confidence level, following the simplified procedure proposed by Moffat [19]. If values of fixed and random errors are available, the overall uncertainty assigned to the measured variable x is given by:

$$\varepsilon_x = \left[ \left( B_{inst} \right)^2 + \left( 2\sigma \right)^2 \right]^{1/2} \tag{1}$$

Otherwise, an overall uncertainty has been estimated on the basis of the manufacturers specifications.

The overall uncertainty assigned to the calculated parameter P is estimated using the root-sum-square propagation rule:

$$\varepsilon_P = \left[ \sum_{i=1}^{N} \left( \frac{\partial P}{\partial x_i} \varepsilon_i \right)^2 \right]^{1/2} \tag{2}$$

The overall uncertainty of the temperature is 0.1 °C, whereas for the positions of the thermocouples is 0.3 mm. The measurement of the time is linked to the internal clock of the PC and it is accurate to 0.16 s.

## 3. Mathematical formulation and numerical solution

The physical system consists of a vertical cylinder of PCM heated from above and cooled from the bottom. The side walls are free to exchange heat with the environment.

**Table 2 -** Thermophysical properties of n-octadecane

| Properties | Value | |
|---|---|---|
| Liquid density | 814 | kg/m$^3$ |
| Solid density | 814 | kg/m$^3$ |
| Liquid thermal conductivity | 0.157 | W/m K |
| Solid thermal conductivity | 0.390 | W/m K |
| Liquid specific heat | 2200 | J/kgK |
| Solid specific heat | 1900 | J/kgK |
| Latent heat of fusion | 241360 | J/kg |
| Melting temperature | 28.18 | °C |

The geometry and the boundary conditions make the problem axisymmetric (excluding any angular dependence in the temperature distribution).

The mathematical model formulated to represent the physical system is based on the following assumptions:

• the PCM is homogeneous and isotropic;
• the thermophysical properties are constant in each phase;
• the phase-change occurs at a single temperature;
• the heat transfer is controlled only by conduction;
• the problem is two-dimensional;
• the difference of density between solid and liquid does not create appreciable local motion of the liquid.

The problem is then governed by the Fourier equation, to be solved for the two phases, solid and liquid (i = s or l for solid or liquid):

$$\frac{\partial}{\partial z}\left(\lambda_i \frac{\partial T_i}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_i r \frac{\partial T}{\partial r}\right)=\frac{\partial\left(\rho_i c_i T_i\right)}{\partial t} \tag{3}$$

The initial condition is given by:

$$T\left(z, r, t=0\right)=T_0\left(z, r\right) \tag{4}$$

The boundary conditions are given by

- cold surface $T=T_b(z=0,r,t)$ $0 \le r \le R,$ $t > 0$ (5)

- hot surface $T=T_t(z=H,r,t)$ $0 \le r \le R,$ $t > 0$ (6)

On the side surface the thermal coupling with the environment is modelled through boundary condition of the third kind:

$$\left[-\lambda \frac{\partial T}{\partial r}\right]_{r=R}=h\left[T-T_e\left(t\right)\right] \qquad 0 \le z \le H,\ r = R,\ t > 0 \tag{7}$$

At the phase-change interface two further conditions must be satisfied. At the solid-liquid interface the energy balance equation can be written in the following form, as proposed by Özisik [20]:

$$\left[1+\left(\frac{\partial Z}{\partial r}\right)^2\right]\left[\lambda_s \frac{\partial T_s}{\partial z}-\lambda_l \frac{\partial T_l}{\partial z}\right]_{z=Z(r,t)}=\rho_s r_f \frac{\partial Z(r,t)}{\partial t} \tag{8}$$

while continuity of temperature is given by:

$$T_s = T_l = T_f \tag{9}$$

Equations (8) and (9) are those typical of the Stefan problem. These consider the release or the storage of energy during the freezing or melting; generally the interface position is unknown a priori. For the numerical solution of the problem Finite Volume Method is used. The numerical procedure and some validation exercises are described in full details in [15]. Here it is relevant to underline that a simplified 2-D approach is followed. Inside each control volume affected by the change of phase, the interface is assumed to advance only in the z direction, neglecting the radial derivative of the interface position, equation (8). The resulting melting/solidification front assumes thence a stepwise shape.

## 4. Results and discussion

Experimental tests were carried out to obtain cyclic processes of melting and freezing in the PCM. An on/off heating was used to produce these cyclic processes. The tests always started by switching on the cooler in order to obtain a steady temperature distribution inside the specimen. After 1 h of data acquisition, a time enough to attain the steady state, the heating system was activated for 7 h, whereupon was disconnected. Successively, the test was continued for 2 periods of on/off heating 16 h long. The data acquisition was then 48 h long. On the bottom a temperature of about 15°C was maintained. The temperature was sampled every 4 min.

Even if strongly very low, the thermal coupling between cylinder and environment was taken into account through an overall heat transfer coefficient equal to 0.5 W/m$^2$K. The external temperature, recorded every two hours, was considered variable in the model and taken into account through a step-wise temperature-time function.

The measured and computed temperature distributions are compared in figure 2. In this figure the symbols TC1 - TC8 refer to the thermocouples of table 1. TC1 and TC8 are those used as the boundary conditions in the mathematical model. The continuous line is due to the high number of samples gathered (15 per hour in the 48 h of sampling). For reason of clarity, in figure 2 for TC2-TC7 just a limited numbers of samples are shown (1 per hour).

On the whole the agreement between experiment and prediction is very good. The presence of an interface that separates an upper zone, where the PCM is liquid, from a lower zone at the solid state, is clearly evident. After the activation of the phase change process, the liquid zone is characterized by faster variations of temperature, whereas in the solid zone this change is slower. At the third on/off cycle a steady periodic state seems to be attained. While on the heater the peaks of temperature and the switching off are exactly in phase, inside the specimen the peaks of temperature move forward in time due to the thermal inertia of the system.

In the liquid phase, the agreement between numerical results and experimental data is very good; the measured temperature is slightly different than that computed. The maximum difference is of 1.66 °C. In the solid phase the agreement seen in the liquid, is lost. The difference between measured and predicted temperatures increases, in particular for TC4. The maximum difference is of 3.23 °C. As already discussed in [16], for periodic heating the quantitative disagreement is less significant than for the case of constant heating [15].

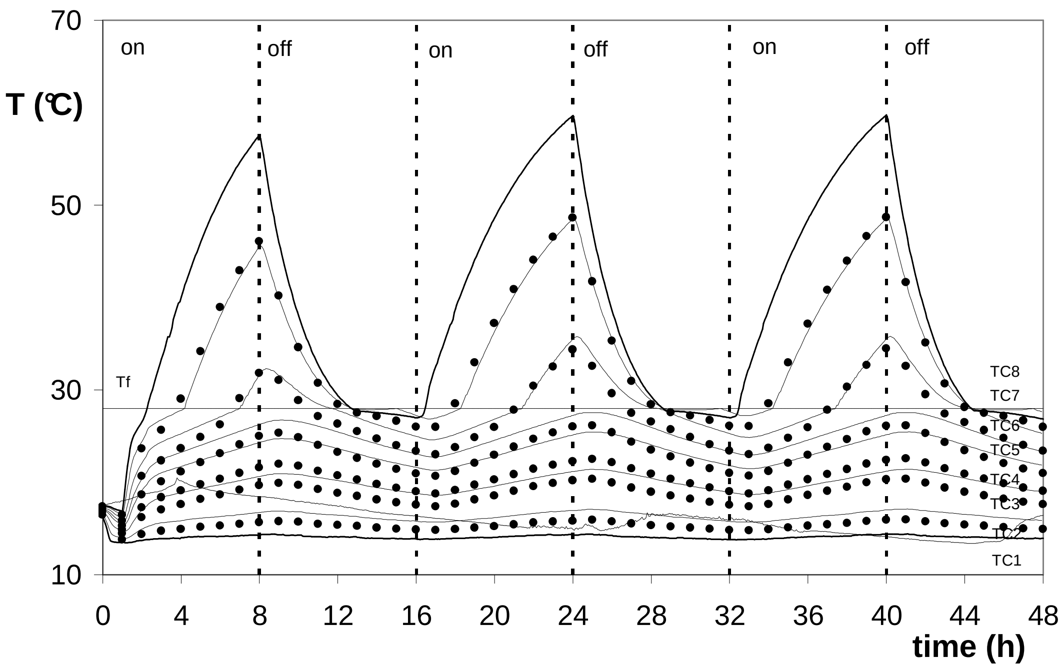


**Figure 2 -** Experimental and numerical comparison of the test (points: experimental data; continuous lines: calculated temperature; dotted line: ambient temperature).

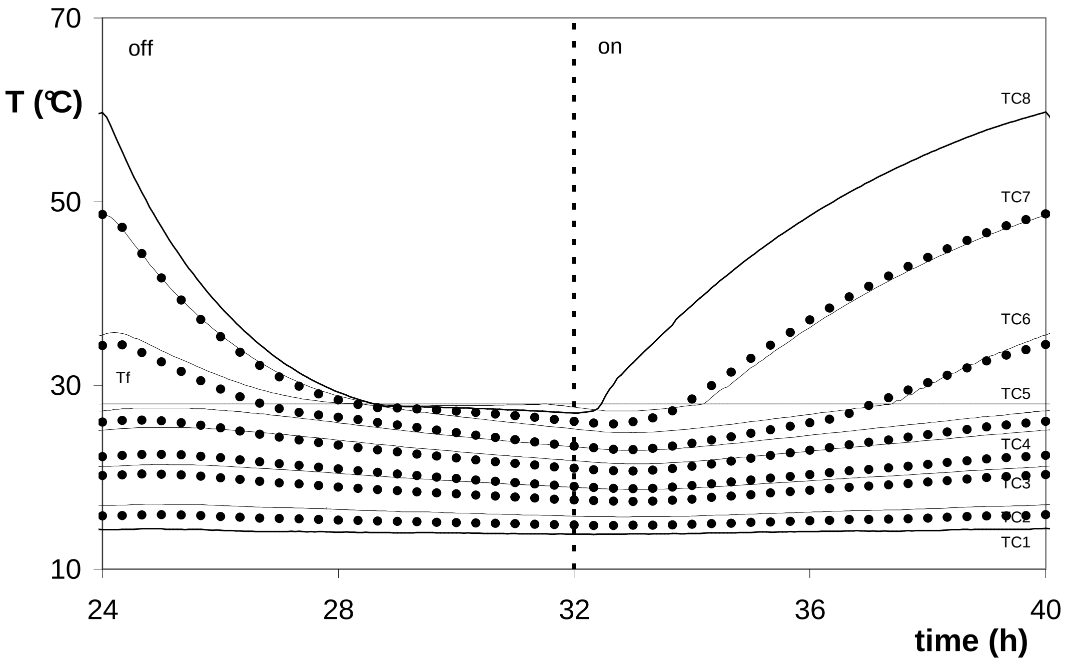


**Figure 3 -** Detail of the experimental and numerical comparison of the test (points: experimental data; continuous lines: calculated temperature; dotted line: ambient temperature).

In the numerical simulation the melting interface moves faster that in the experiment. This can be easily explained by a literature value of the latent heat of fusion [18] higher than expected. It is enough to reduce the latent heat of a 10% to improve the comparison.

As can be seen in figure 3, where a detail of the final period is shown, in the numerical simulation, during cooling, in particular when the specimen returns completely solid, TC7 becomes hotter than TC8, that used to impose the boundary condition. This is probably due to a real melting temperature lower than that proposed in the literature [18]. In figure 2 the experimental melting temperature seems to be about 27°C. It is enough to reduce this value in the model up to 27°C to improve the comparison.

The solid-liquid phase change interests only the first two thermocouples near the heater. This means that the latent heat storage allows to maintain two thirds of the sample under the melting point. This is because the great part of the heat flux introduced in the sample via the heater is used for the advancement of the interface and only a limited amount of this flux is still available for the heating of the remaining solid.

The coexistence of more phase change surfaces was not detected. This is due to the constant cooling of the bottom; the heat flux is never extracted from the top surface and the solid phase is significantly sub-cooled at the beginning of the experiment.

As experienced in [16], also for this steady-periodic heating the assumption to neglect the natural convection in the liquid phase gives rise to numerical results and experimental data in very good accordance, in the liquid region. Conversely, for a constant heating [22] the effect of natural convection is found to be predominant. As suggested by Hasan *et al.* [21] for a similar experimental arrangement but for a different heating scheme, the prevailing role played by the conduction is confirmed. It seems that the steady-periodic heating could be able to control and reduce the occurrence of natural convection in the liquid phase due to the thermal coupling with the environment through the side walls of the cylinder.

The distributions of latent, sensible and total heat storage per unit area, calculated with the mathematical model, are shown in figure 4. Here the two almost overlapped curves represent the total heat storage calculated both as the time integration of the difference between input and output heat fluxes, and as the time accumulation of internal energy and latent heat in each control volume.

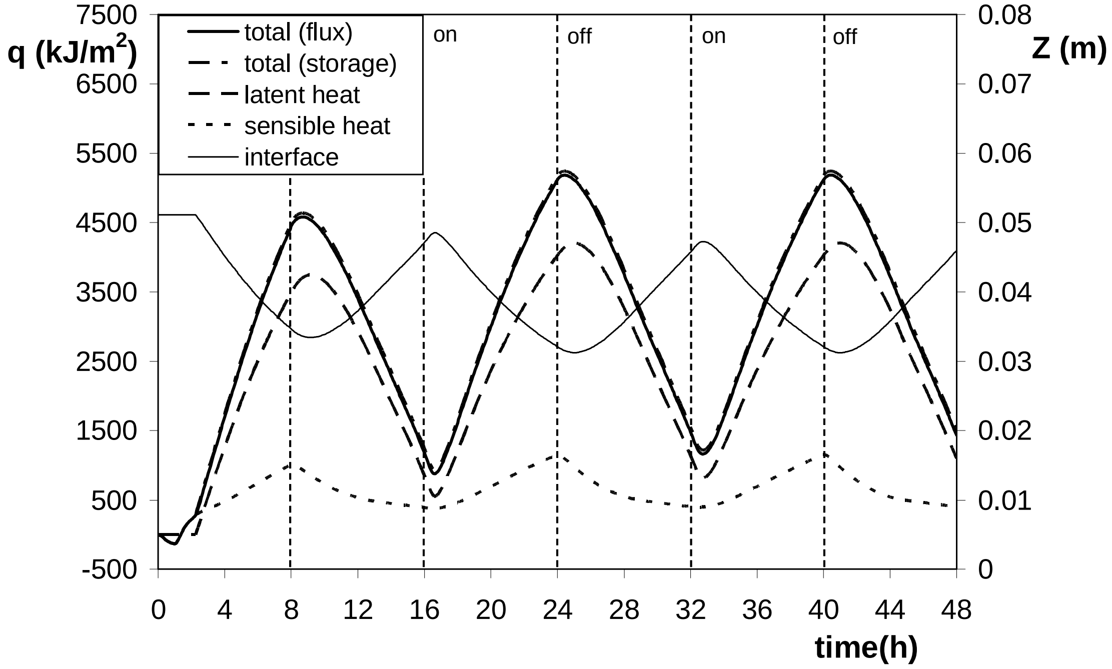


**Figure 4 -** Energy storage

The maximum amount of stored latent heat is about four times the sensible one. The maximum of sensible heat storage is in phase with the on/off heating. The maximum of latent heat storage is strictly correlated to the advancement of the solid-liquid interface. This interface moves also after the stop of the heating, due to the energy available above the melting interface.

In figure 4 the calculated position of the melting interface in r = 0.016 m is also shown. As already anticipated in the discussion of figure 2, the periodic movements of the interface produce the melting and freezing of 19.9 mm of PCM. This is due to the low thermal conductivity of the PCM. In the practical applications an enhancement of this parameter, for instance with fins, is mandatory.

Even if the specimen is heated with an on/off heat flux, in the model the boundary condition on the heater is of "assigned temperature". This choice is due to the high thermal inertia of the heater, obtained with a thick layer of copper, and to the heat dissipation through the copper walls of the heater. It was impossible to quantify the true amount of heating of the specimen and its time distribution. For this reason as the boundary condition the effect of the heating on the PCM, that is the temperature, was used.

## 5. Concluding remarks

A two-dimensional phase-change problem for which conduction is prevalent on the other heat transfer effects has been investigated experimentally and numerically. The process is characterized by an on/off heating.

The measured and calculated distributions of temperature are in good accordance. In this comparison only minor discrepancies arise. For this comparison, a very good knowledge of the thermal properties of the PCM is important. However, this is difficult to be obtained, because these properties are strongly dependent on the purity of the PCM, with large range of variations [22].

The analysis of the energy behaviour of the system shows that the energy stored oscillates in time with the on/off boundary condition.

In general it can be observed that PCM based TCUs are suitable to be used when high powers act in short times. After a peak of power a phase change can occur and the storage system has the possibility to release the stored energy with a freezing process.

Finally, the numerical code demonstrated to be an effective tool to analyse the energy behaviour of a storage system in those applications characterized by on-off heating.

**Nomenclature**

| | | |
|---|---|---|
| B | fixed error | |
| c | specific heat | J/(kgK) |
| h | heat transfer coefficient | W/(m$^2$K) |
| H | specimen height | m |
| P | calculated parameter | |
| q | heat per unit area | J/m$^2$ |
| R | specimen radius | m |
| r | radial coordinate | m |
| $r_f$ | latent heat of fusion | J/kg |
| t | time | h |
| T | temperature | °C |
| x | measured variable | |
| z | axial coordinate | m |
| Z | interface position | m |

Greek symbols

| | | |
|---|---|---|
| $\varepsilon$ | overall uncertainty | |
| $\lambda$ | thermal conductivity | W/(m K) |
| $\rho$ | density | kg/m$^3$ |
| $\sigma$ | random errors | |

Subscripts

| | |
|---|---|
| b | bottom |
| e | environment |
| f | melting |
| H | hot surface |
| inst | instrument |
| l | liquid |
| P | calculated parameter |
| r | radial |
| s | solid |
| t | top |
| x | measured variable |
| 0 | cold surface |

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