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An experimental study of enhanced heat transfer in rectangular PCM thermal storage

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Abstract

The heat-transfer characteristics of a latent-heat storage unit with a finned surface have been experimentally studied in terms of the solidification and melting processes by comparing them with those of a heat-storage unit with a plain surface. Paraffin with a melting point of 30 °C was used in the investigations because it is appropriate for thermal storage applications in buildings. Time-based variations of the temperature distributions and heat flux are explained from the results of observations of the melting and the solidification layers. The dimensionless Nusselt number was calculated as a function of the Rayleigh number for natural convection in the paraffin for both the melting and the solidification processes. The effectiveness of the fins was calculated from the quotient of the heat flux with fins and the heat flux without fins.

1. Introduction

Thermal storage systems designed for the heating and cooling of buildings (HVAC applications) and hot-water preparation are becoming increasingly important due to limited fossil-fuel reserves and the need to protect the environment. Thermal storage for HVAC applications can involve storage at various temperatures associated with heating and cooling processes [1]. High-temperature storage is typically associated with solar energy, waste-heat utilization or heat-pump applications, whereas cool storage is associated with air-conditioning, refrigeration, or cryogenic-temperature processes.

A technology that can be used to store large amounts of heat or cold in a defined volume has been the subject of research for a long time. One of the possibilities is to use a phase-change material (PCM) as the thermal storage media. Phase-change materials were first used in British trains to prevent them from becoming too cold. The first reports of a PCM described in the literature were applications for heating and cooling in buildings, by Telkes in 1975 [2], and Lane in 1986 [3]. In 1978 Telkes [4] published the idea of using PCMs in walls; however, these are better known as Trombe walls. Bordeau [5] tested a passive solar collector containing $CaCl_2 \cdot 6H_2O$. He found that an 8.1-cm PCM wall has a better thermal accumulation than a 40-cm concrete wall. An interesting possibility in building applications is the impregnation of PCMs into porous construction materials, e.g. plasterboard, to increase their thermal mass [6–8].

PCMs have also been developed to store "coolness" for air-conditioning applications: the "cold" is collected and stored in the PCM during the night, and then the PCM is used to cool the interior of a building during the hottest hours of the day. This concept is known as free-cooling [9–12].

Since the thermal conduction of PCMs is low, several methods exist to enhance the transfer of the heat. The use of finned tubes with different configurations has been proposed by various researchers, these include: Abhat et al. [13], Marcos [14], Sadusuke and Naokatsu [15], Costa et al. [16], Padmanabhan and Krishna Murthy [17], Velraj et al. [18,19] and Ismail et al. [20].

Several other heat-transfer enhancement techniques have also been reported. Siegel [21] studied improvements in the solidification rate for molten salt containing a dispersion of high-conductivity particles. Another

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Nomenclature

a	temperature conductivity (m^2/s)	T	temperature (K)
Bi	Biot number(–)	V	volume (m^3)
c_p	specific heat at constant pressure (J/kg K)	x	coordinate (m)
D	distance between fins (m)	X	dimensionless coordinate (–)
Fo	Fourier Number (–)	y	coordinate (m)
h	specific enthalpy (J/kg)	Y	dimensionless coordinate (–)
l	length (m)	z	coordinate (m)
L	paraffin depth (m)		
m	mass (kg)	*Greek symbols*	
q	specific heat (J/kg)	α	thermal convection coefficient (W/m^2 K)
q_t	fusion heat (J/kg)	λ	thermal conductivity (W/m K)
Q	heat (J)	ρ	density (kg/m^3)
Ste	Stefan number (–)	ϕ	heat flux (W)
t	time (s)		

method was to embed the PCM in a metal-matrix structure [22–26]. And the use of thin aluminium plates filled with a PCM was developed by Bauer and Wirtz [27].

Mehling and co-workers [28–31] and Py et al. [32] proposed a graphite compound material, where the PCM is embedded inside a graphite matrix. The main advantage of such a material is the increased heat conductivity in the PCM without much of a reduction in the energy storage, but other advantages include a decrease in the subcooling of salt hydrates and a decrease in the volume change of the paraffins.

There are a lot of PCM applications where rectangular thermal storage is needed. One of them is a solar PCM storage wall for ventilating buildings [33]. The experiments described in the rest of this paper will explain the physical process of heat transfer in this rectangular storage.

2. Experimental setup

An experimental setup for the analysis of heat transfer was installed in the laboratory.

Rectangular thermal storage is used when it is possible to transfer heat via a water heat exchanger on one wall of the thermal storage, as shown in Fig. 1. The heat storage (1) has dimensions of $650 \times 500 \times 120$ mm. On one wall there is a heat exchanger (2) where heat can be transferred from the water to the PCM (melting) or vice versa (solidification). The outlet (3) and the inlet (4) for the water are connected with pipes. The water flows from an aqueduct (7) through a rotameter (6) into the electric heater (5) or directly into the experimental device (2). The thermal storage is insulated with polystyrene that has a thermal conductivity of $\lambda = 0.038$ W/m K.

By measuring the volume flow of the water together with the inlet and outlet temperatures it is possible to

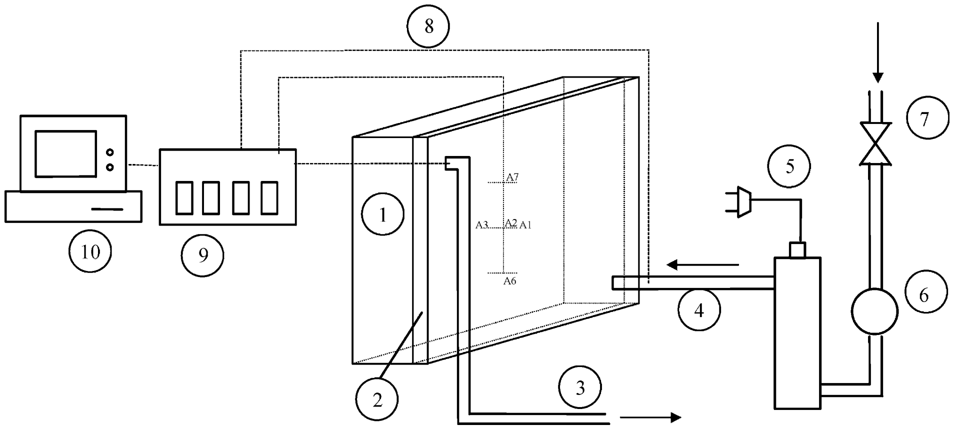

Fig. 1. Rectangular thermal storage with experimental setup.

analyse the heat in to (and out of) the heat store. The signals from the thermocouples marked in Fig. 1 with $A_{(x)}$ (8) are fed to the ADAM module (9) and stored in a PC (10).

The experiments were conducted in such a way that the melting and solidification were carried out once with fins and once without fins, in order to determine the enhancement effect of the fins. RUBITHERM RT 30 paraffin was used for the tests. Fig. 2 shows a DSC analysis of this paraffin.

The fins for the heat-transfer enhancement were made of steel with a thermal conductivity $\lambda = 20$ W/m K. The 32 fins were rectangular, and had the following dimensions: height 0.5 m, length 0.12 m, thickness 1 mm.

A panel with fins is presented in Fig. 3:

The temperatures were measured with type-K thermocouples (NiCr–Ni). These thermocouples were thin (0.6×1.0 mm) because the temperatures were measured in the paraffin. The measurement uncertainty, as described by the standard IEC 584-2, was ±0.5 °C.

The temperatures of the inlet and the outlet water were also measured. Using this data the heat flux was calculated with the following equation:

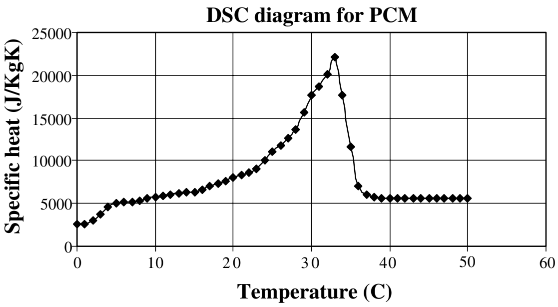

Fig. 2. DSC diagram for analysed PCM Rubitherm RT 30.

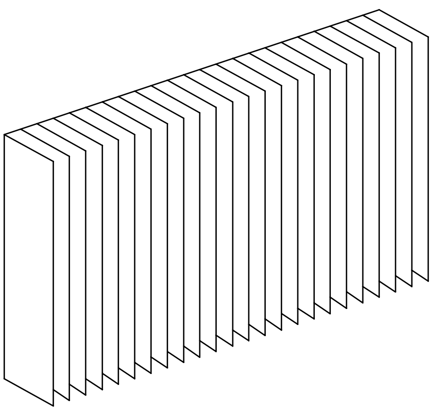

Fig. 3. Fins for heat-transfer enhancement analysis.

$$\phi = \dot{m} c_p \Delta T \tag{1}$$

The measurement uncertainty of the heat flux is as follows:

$$M_\phi = \left[\left(\left(\frac{\partial \phi}{\partial m} \right) M_{\mathrm{m}} \right)^2 + \left(\left(\frac{\partial \phi}{\partial c_p} \right) M_{c_p} \right)^2 + \left(\left(\frac{\partial \phi}{\partial \Delta T} \right) M_{\Delta T} \right)^2 \right]^{1/2} \tag{2}$$

where

$$\frac{\partial \phi}{\partial m} = c_p \Delta T, \quad \frac{\partial \phi}{\partial c_p} = m \Delta T, \quad \frac{\partial \phi}{\partial \Delta T} = m c_p \tag{3}$$

By combining Eq. (3) with (2) we obtain:

$$M_\phi = ((c_p \Delta T M_{\mathrm{m}})^2 + (m \Delta T M_{c_p})^2 + (m c_p M_{\Delta T}))^2 \tag{4}$$

and dividing Eq. (4) by Eq. (1) gives us:

$$\frac{M_\phi}{\phi} = \left[\left(\frac{M_{\mathrm{m}}}{m} \right)^2 + \left(\frac{M_{c_p}}{c_p} \right)^2 + \left(\frac{M_{\Delta T}}{\Delta T} \right)^2 \right]^{1/2} \tag{5}$$

$$\frac{M_\phi}{\phi} = \sqrt{0.0125^2 + 0.005^2} = 0.0135 \tag{6}$$

The measurement uncertainty of the testing line was ±1.35%.

3. Results and discussion

The experiments were made for the following reasons:

- to determine the temperature distribution in the heat storage,
- to test the changing interface position between the solid and the liquid,
- to analyse the process of heat transfer in the heat storage,
- to determine the process of charging and discharging of the heat storage.

Heat transfer in latent-heat storage is very complex. The process is non-stationary, there is also a phase-change problem, and the process is non-homogeneous because of the fins. Time-dependent charging and discharging of the process is the most important for solar-energy applications.

The results are presented in two parts: first, the results of the melting; and second, the results of the solidification.

3.1. Melting

The melting of the paraffin without fins is presented first. The measurements began with the temperature of

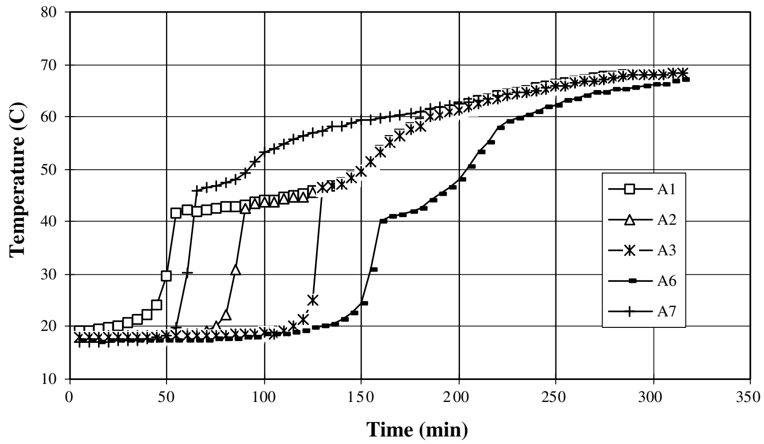

Fig. 4. Melting of the paraffin without fins.

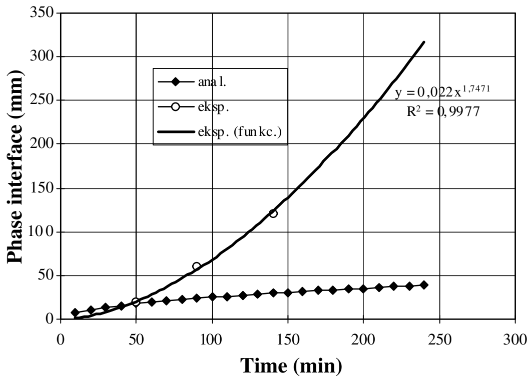

Fig. 5. Phase-change interface position.

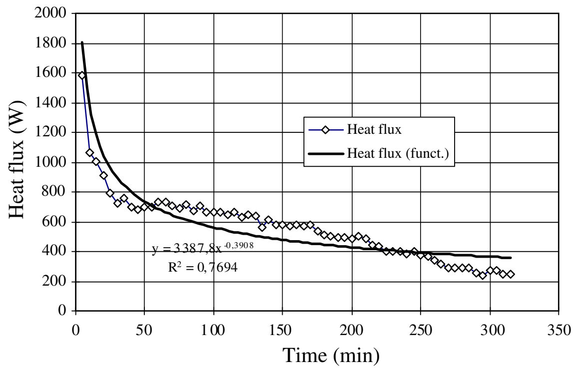

Fig. 6. Heat flux at heating without fins.

thermal storage at room temperature. Next, hot water at 65 °C was fed into the heat exchanger. Temperatures were measured at five main points, and the results are presented in Fig. 4. From the results we can see that the phase transformation takes place at points where the line is no longer smooth.

Fig. 5 shows the comparison of the measured phase-change interface position with the analytical results (conduction). From the results we can see that the data can only be compared at the beginning of the process. The reason for this is natural convection, which increases the heat transfer.

The measured heat flux into the heat storage can be calculated from the inlet and outlet temperatures of the water, and is presented in Fig. 6. From the integration of this heat flow we could obtain a value for the heat that was stored in the paraffin.

Heat transfer is described with the Nusselt number, which is a function of various parameters. During natural convection the Rayleigh number ($Ra = Gr * Pr$) is the main parameter. On the basis of the experimental data, a correlation for the heat transfer in the heat storage can be written as:

$$Nu = 8 \times 10^{-12} Ra^{1.0392} \tag{7}$$

where the following equations have been used [34].

$$Nu = \frac{\alpha l}{\lambda} \tag{8}$$

$$\alpha = \frac{\phi}{A(T_w - T_t)t} = \frac{\int_0^t \phi(t)\,dt}{A(T_w - T_t)} \tag{9}$$

$$Ra = Gr * Pr = \frac{g l^3 (T_w - T_t)}{\nu^2} * \frac{\nu}{a} \tag{10}$$

The melting of the paraffin with and without fins under the same conditions is presented in Fig. 7, which shows the temperature variations.

The heat flux as a function of time was also measured for the melting of the paraffin with fins. To compare the heat transfer with and without fins a quotient of both

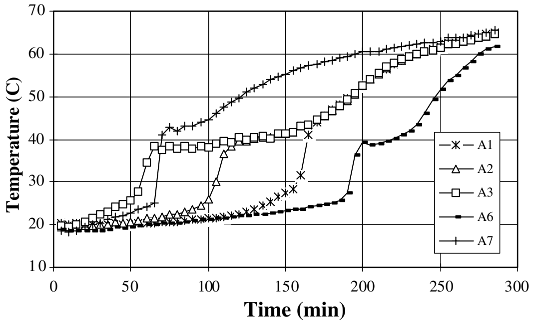

Fig. 7. Melting of the paraffin with fins.

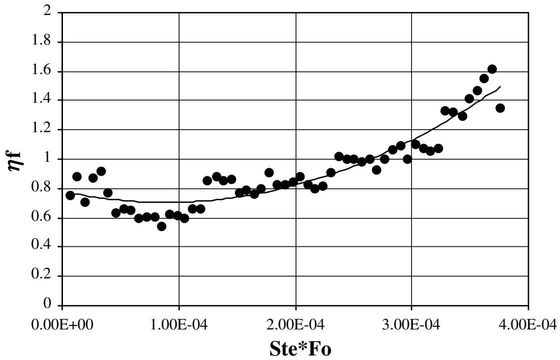

Fig. 8. Fin effectiveness at melting of the paraffin.

heat fluxes was made. This is referred to as the fin effectiveness (Eq. (11)):

$$\eta_{\mathrm{f}} = \frac{\dot{q}_{\mathrm{fin}}}{\dot{q}_{\mathrm{without\ fin}}} \tag{11}$$

This ratio is a function of time and is presented in Fig. 8 in dimensionless form (τ): where dimensionless time is written as a multiplication of the Stefan and Fourier numbers, as in Eq. (12):

$$\tau = \frac{c_p(T_{\mathrm{s}} - T_{\mathrm{t}})}{q_{\mathrm{t}}} \frac{\alpha t}{H^2} = Ste * Fo \tag{12}$$

The approximation of the function is written in the following equation ($R^2 = 0.87$):

$$\eta_{\mathrm{f}} = 1 \times 10^7 * (Ste \cdot Fo)^2 - 1719.4 \cdot (Ste \cdot Fo) + 0.7813 \tag{13}$$

From the results it can be seen that for a low Fourier number the ratio is less than 1. The reason for this is that natural convection, which is dominant because of the melting, is reduced because of the fins.

3.2. Solidification

The solidification of the paraffin without the fins is presented in Fig. 9. The experiment was made with the cooling of the melted paraffin from Fig. 4. Cold water at 18 °C was fed through the storage and the result of the temperature change of the paraffin shows us the interface position.

Solidification is a process where natural convection can be neglected in comparison with melting. This can be seen from Fig. 10, where the measured data are compared with the analytical data (conduction).

The comparison is good, and the conclusion could be that solidification can be modelled only by conduction (λ). Similar results were also obtained by other authors, and these can be found in the literature. This can also confirm the dimensionless equation (14):

$$Nu = 7 \times 10^{-13} Ra^{0.9364} \tag{14}$$

A comparison of Eq. (14) with Eq. (7) shows that natural convection in the case of melting is more than 10 times higher than during solidification.

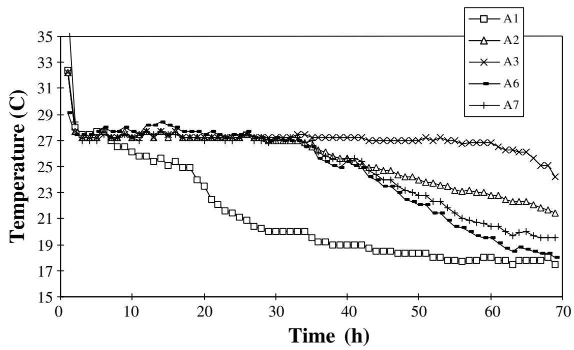

Fig. 9. Temperature variations at solidification of the paraffin.

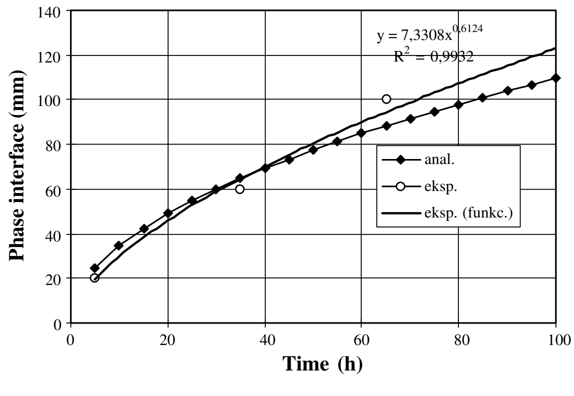

Fig. 10. Phase-change interface position at solidification without fins.

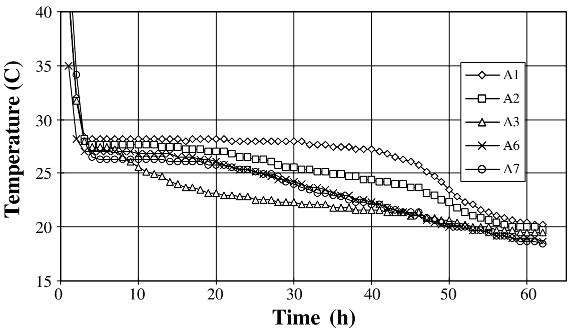

Fig. 11. Solidification of the paraffin with fins.

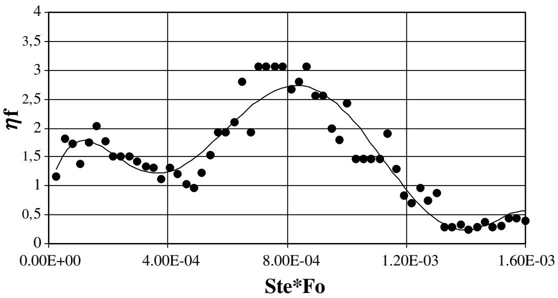

Fig. 12. Fin effectiveness at solidification with fins.

The solidification of the paraffin with the fins is presented in Fig. 11. The temperature variation shows a typical solidification process. The lines are very steep at the beginning, after which there is a change in the incline because the heat is extracted as latent heat and not as sensible heat (ΔT).

The fin effectiveness, which is presented in Fig. 12, shows that the value increases up to 3.06 and then decreases. The same results were also obtained by other authors [35]. It is obvious that the heat transfer during solidification is greater if fins are included. In our case a 40% reduction in the solidification time was calculated.

The functional dependence of the fin efficiency is presented with Eq. (15) ($R^2 = 0.787$):

$$\eta_f = -2 \times 10^6 \cdot (Ste \cdot Fo)^2 + 3000.4 \cdot (Ste \cdot Fo) + 1.0567 \tag{15}$$

4. Conclusion

Melting and solidification are physical processes that are used in different areas: in the food industry (the freezing of food), in metallurgy and in heat-storage processes.

There are many different ways to investigate these processes. The oldest is the analytical principle, which gives us an equation for the temperature distribution in terms of place and time. Since ideal cases are not often found in the nature, numerical methods that provide us with temperature and velocity fields can also be used. However, because of the complexity of systems, experiments are usually one of the best ways in which we can obtain a measure of the real performance of a process.

We analysed the heat-transfer enhancement in a phase-change material in the Laboratory for Heating, Sanitary and Solar Technology at the Faculty of Mechanical Engineering in Ljubljana. The heat storage with a phase-change material was made with a heat exchanger where the heat could be transferred from the heat-transfer media (water) to the phase-change material.

Measurements were made on the melting and solidification of paraffin, and the time-dependent storage of heat in the PCM with and without fins for heat-transfer enhancement was analysed. The results were presented in terms of temperature and heat flux as a function of time.

A new correlation between the dimensionless numbers (Nusselt number as a function of Rayleigh number) was made. A comparison of the equations for melting and freezing shows that natural convection is present during melting and increases the heat transfer. During solidification, conduction is the dominant form of heat transfer. We can conclude that heat storage (melting) is not a problem during thermal storage applications, and that the extraction of heat (solidification) can be effectively enhanced with fins.

The fin effectiveness was also investigated. It was found that for a low Fourier number the ratio is less than 1. The reason for this is that natural convection, which is dominant during melting, is reduced because of the fins. The fin effectiveness during solidification shows that the value is increasing up to 3.06 and is then decreasing. This shows that heat transfer during solidification is greater if the fins are included. In our case a 40% reduction in the solidification time was calculated.

Acknowledgements

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References

[1] ASHRAE HANDBOOK, HVAC Applications SI Edition, 1999.
[2] M. Telkes, Thermal storage for solar heating and cooling, in: Proceedings of the Workshop on Solar Energy Storage

Subsystems for the Heating and Cooling of Buildings, Charlottesville, Virginia, USA, 1975.
[3] G.A. Lane, Solar Heat Storage: Latent Heat Material, vol. II, Technology, CRC Press, Florida, 1986.
[4] M. Telkes, Trombe wall with phase change storage material, in: Proceedings of the 2nd National Passive Solar Conference, Philadelphia, PA, 1978.
[5] L.E. Bordeau, Study of two passive solar systems containing phase-change material for thermal storage, in: Proceedings of the 5th National Passive Solar Conference, 1980.
[6] M.M. Shapiro, D. Feldman, D. Hawes, D. Banu, PCM thermal storage in wallboard, in: Proceedings of the 12th Passive Solar Conference, Portland, Oregon, USA, 1987.
[7] I.O. Salyer, A.K. Sircar, R.P. Charloff, Advanced phase-change materials for passive solar storage applications, in: Proceedings of the Solar Building Conference, Silver Spring, Washington, D.C., USA, 1985.
[8] K. Peippo, P. Kauranen, P.D. Lund, A multicomponent PCM wall optimized for passive solar heating, Energy Buildings 17 (1991) 259–270.
[9] B. Zalba, Free-cooling, an application of PCMs in TES, Ph.D. Thesis, University of Zaragoza, Spain, 2002.
[10] S.M. Vakilaltojjar, W. Saman, Analysis and modeling of a phase change storage system for air conditioning applications, Appl. Thermal Eng. 21 (2001) 249–263.
[11] S.M. Vakilaltojjar, W. Saman, Domestic heating and cooling with thermal storage, in: Proceedings of Terrastock, Stuttgart, Germany, 2000.
[12] F. Bruno, W. Saman, Testing of a PCM energy storage system for space heating, in: Proceedings of the World Renewable Energy Congress VII, Cologne, Germany, 2002.
[13] A. Abhat, S. Aboul-Enein, N. Malatidis, Heat of fusion storage systems for solar heating applications, in: C. Den Quden (Ed.), Thermal Storage of Solar Energy, Martinus Nijhoff, 1981.
[14] V.H. Marcos, Investigation of latent heat thermal energy storage system, Solar Wind Technol. 7 (2/3) (1990) 197–202.
[15] I. Sadasuke, M. Naokatsu, Heat transfer enhancement by fins in latent heat thermal energy storage devices, Solar Eng., ASME (1991) 223–228.
[16] M. Costa, D. Buddhi, A. Oliva, Numerical simulation of latent heat thermal energy storage system with enhanced heat conduction, Energy Convers. Manage. 39 (3/4) (1998) 319–330.
[17] P.V. Padmanabhan, M.V. Krishna Murthy, Outward phase change in a cylindrical annulus with axial fins on the inner tube, Int. J. Heat Mass Transfer 29 (1986) 1855–1868.
[18] R. Velraj, R.V. Seeniraj, B. Hafner, C. Faber, K. Schwarzer, Experimental analysis and numerical modelling of inward solidification on a finned vertical tube for a latent heat storage unit, Solar Energy 60 (1997) 281–290.
[19] R. Velraj, R.V. Seeniraj, B. Hafner, C. Faber, K. Schwarzer, Heat transfer enhancement in a latent heat storage system, Solar Energy 65 (1999) 171–180.
[20] K.A.R. Ismail, C.L.F. Alves, M.S. Modesto, Numerical and experimental study on the solidification of PCM around a vertical axially finned isothermal cylinder, Appl. Thermal Eng. 21 (2001) 53–77.
[21] R. Siegel, Solidification of low conductivity material containing dispersed high conductivity particles, Int. Heat Mass Transfer 20 (1977) 1087–1089.
[22] M. Kamimoto, Y. Abe, S. Sawata, T. Tani, T. Ozawa, Latent heat storage unit using form-stable high density polyethylene for solar thermal applications, in: Proceedings of the International Symposium on Thermal Application of Solar Energy, Hakone, Kanagawa, Japan, 1985.
[23] C.J. Hoogendoorn, G.C.J. Bart, Performance and modelling of latent heat stores, Solar Energy 48 (1992) 53–58.
[24] M.A. Khan, P.K. Rohatgi, Numerical solution to a moving boundary problem in a composite medium, Numer. Heat Transfer 25 (1994) 209–221.
[25] X. Tong, J. Khan, M.R. Amin, Enhancement of heat transfer by inserting a metal matrix into a phase change material, Numer. Heat Transfer, Part A 30 (1996) 125–141.
[26] X. Tong, J.A. Khan, M.R. Amin, Enhancement of heat transfer by inserting a metal matrix into a phase change material, Numer. Heat Transfer, Part A 30 (1996) 125–141.
[27] C.A. Bauer, R.A. Wirtz, Thermal characteristics of a compact, passive thermal energy storage device, in: Proceedings of the 2000 ASME IMECE, Orlando, Florida, USA, 2000.
[28] P. Satzger, B. Exka, F. Ziegler, Matrix-heat-exchanger for a latent-heat cold-storage, in: Proceedings of Megastock '98, Sapporo, Japan, 1998.
[29] H. Mehling, S. Hiebler, F. Ziegler, Latent heat storage using a PCM-graphite composite material: advantages and potential applications, in: Proceedings of the 4th Workshop of IEA ECES IA Annex 10, Bendiktbeuern, Germany, 1999.
[30] H. Mehling, S. Hiebler, F. Ziegler, Latent heat storage using a PCM-graphite composite material, in: Proceedings of Terrastock 2000—8th International Conference on Thermal Energy Storage, Stuttgart, Germany, 2000, pp. 375–380.
[31] L.F. Cabeza, H. Mehling, S. Hiebler, F. Ziegler, Heat transfer enhancement in water when used as PCM in thermal energy storage, Appl. Thermal Eng. 22 (2002) 1141–1151.
[32] X. Py, R. Olives, S. Mauran, Paraffin/porous-graphite-matrix composite as a high and constant power thermal storage material, Int. J. Heat Mass Transfer 44 (2001) 2727–2737.
[33] U. Stritih, P. Novak, Solar energy storage in phase change material, The Second ISES Europe Solar Congress, Eurosun 98, Slovenia, 1998.
[34] D. Streit, Free convection on horizontal pipe with stone/water filling with making and melting of ice, Doctoral dissertation, mentor E. Hahne, University of Stuttgart, 1996.
[35] K. Sasaguchi, H. Imura, Heat transfer characteristics of a latent heat storage unit with a finned tube 1st report: experimental studies on solidification and melting processes, Bull. JSME 29 (255) (1986).