



Parametric Study for PCM-Based Heat Sinks: A Numerical Investigation

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Abstract. Studying thermal management of mechatronic components presents a great challenge for researchers in several domains in the last few decades. In most cases, classical cooling systems may not be sufficient. To this end, phase change material-based heat sinks are well recommended for a passive cooling problem. In this paper, we present an efficient thermal energy management of a PCM-based round pin-finned heat sink that leads to provide its optimal configuration. The numerical results compare relatively well with that of the experimental. A detailed parametric study is based on the effect of several uncertain parameters which are in relation with boundary conditions, geometry and materials. This study leads to determine that salt hydrate has the ability to store more thermal energy of the presented cooling system comparing to n-Eicosane and paraffin wax. Furthermore, a heat sink with a 2 mm pin diameter presents the optimal heat sink geometry for the charging phase under a uniform heat flux about 2800 W/m^2 . Also, increasing the input heat power leads to decrease the latent heating period and then decreasing the ability to store a high amount of thermal energy. Finally, the parametric study leads to determine an optimal configuration with an efficient thermal energy behavior. Thermal performance of each configuration is determined for the charging phase of the electronic device.

Keywords: Thermal energy storage · PCM-based heat sink · Finite element analysis · Heat flux · Latent heating phase

1 Introduction

Recently, thermal energy storage presents the most important factor for researchers in several domains, particularly in the field of mechatronics such

as smartphones, laptops automobile and even planes. Due to the development of new technologies, devices packages become even smaller. In fact, an overheating of electronic components may lead to reduce their lifetime or even their failure. For this reason, a good thermal energy management is extremely needed to avoid its deterioration.

In this context, classical cooling methods are not sufficient. Therefore, many methods of passive cooling by heat dissipation are developed and some of them are based on Phase Change Materials (PCM) [1–3]. In fact, it has been confirmed that PCMs are more efficient particularly with components that operate intermittently [4]. Recently, PCM-based heat sink is recommended to increase the performance of the cooling system as well as to extend its lifetime. In fact, PCMs are characterized by their high latent heat of fusion, high specific heat and very small variation in volume during the phase change. It can be noted also that PCMs have the ability to store a large quantity of thermal energy benefiting from its thermophysical properties and then to release it back later. An experimental investigation is studied by Arshad et al. [1] to ensure and improve the functionality and reliability of the installed structures. In this study, a parametric analysis is proposed to ameliorate the thermal behavior of PCM-based heat sink by changing the diameter of pin-fin as well as PCM volume fraction at different heat fluxes. In [5, 6], a Reliability-Based Design Optimization (RBDO) studies are developed in order to determine an efficient and optimal model of a PCM-based heat sink cooling system where 2D and 3D Finite Element Analysis (FEA) are established respectively.

In this paper, a parametric analysis is proposed to determine an optimal model of PCM-based round pin-fin heat sink. This study is verified and validated experimentally [1]. It consists in comparing the thermal behavior of the proposed PCM-based heat sink for charging phase when changing: input power level, heat sink geometry, PCM thermo-physical properties as well as its volume fraction. Finally, an optimal and efficient configuration is then proposed and it presents an efficient thermal energy management.

2 Studied Cooling System Model: Governing Equations

The thermal energy generated by the heat source is transmitted to all heat sink surfaces. In fact, PCMs have the ability to absorb and store thermal energy during the charging phase until its total melting. For the discharging phase, the stored thermal energy will be dissipated in the ambient air by convection and radiation.

• Energy conservation equation

PCM thermophysical properties are supposed independent of temperature. It can be assumed that only conduction equation is considered, as follow:

$$\frac{\partial}{\partial t} (\rho C_p T) = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(\lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(\lambda \frac{\partial T}{\partial z} \right) + S_h. \quad (1)$$

Note that C_p , ρ and λ are the specific heat, the density and the thermal conductivity, respectively.

The latent heat storage can be defined by the energy source term S_h due to melting and it can be written as follow:

$$S_h = -\frac{\partial}{\partial t}(\rho\Delta H) \quad (2)$$

The sum of the latent heat ΔH and specific enthalpy h_s presents the total enthalpy of PCM:

$$H = \Delta H + h_s. \quad (3)$$

And the specific enthalpy h_s is mathematically defined by:

$$h_s = h_{s,ref} + \int_{T_{ref}}^T C_p dT. \quad (4)$$

In addition, the latent heat ΔH can be defined by:

$$\Delta H = \beta L_f \quad \text{where} \quad \beta = \begin{cases} 0 & \text{if } T \leq T_{sol} \\ \frac{T - T_{sol}}{T_{mel} - T_{sol}} & \text{if } T_{sol} < T < T_{mel} \\ 1 & \text{if } T \geq T_{mel} \end{cases} \quad (5)$$

Note that, β and L_f present the liquid fraction and the latent heat of fusion of PCM.

• Mass conservation

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (6)$$

Note that u , v and w are the velocity components in x , y and z directions, respectively.

• Momentum conservation

$$\rho \left(\frac{\partial u}{\partial t} + \frac{\partial u^2}{\partial x} + \frac{\partial(uv)}{\partial y} + \frac{\partial(uw)}{\partial z} \right) = -\frac{\partial P}{\partial x} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + S.u \quad (7)$$

$$\rho \left(\frac{\partial v}{\partial t} + \frac{\partial(uv)}{\partial x} + \frac{\partial v^2}{\partial y} + \frac{\partial(vw)}{\partial z} \right) = -\frac{\partial P}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) + S.v \quad (8)$$

$$\rho \left(\frac{\partial w}{\partial t} + \frac{\partial(uw)}{\partial x} + \frac{\partial(vw)v^2}{\partial y} + \frac{\partial w^2}{\partial z} \right) = -\frac{\partial P}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right) + S.w + \rho g\alpha_w (T - T_s) \quad (9)$$

3 Numerical Results: Physical Description of the Problem

A detailed 3D design is presented in Fig. 1 of the studied PCM-based round pin-fin heat sink. It is composed by 11×12 pins heat sink matrix with an overall dimension of $114 \times 114 \times 25 \text{ mm}^3$. It is made from aluminum which is characterized by its high thermal conductivity and its lower density.

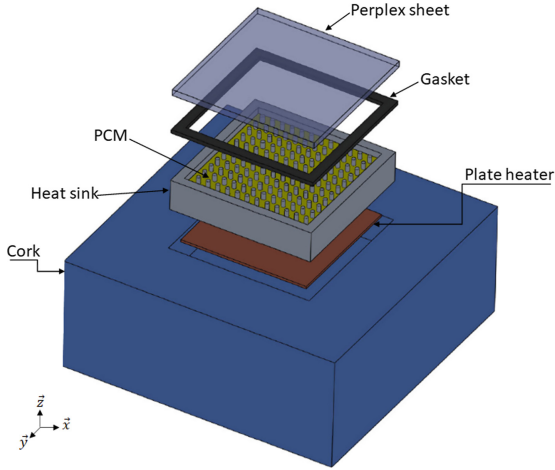


Fig. 1. PCM-based heat sink model: a 3-D assembly.

To minimize thermal losses, an insulator is applied to exterior heat sink walls, except the superior area. The top surface of the heat sink is covered using perperx sheet and silicon gasket for monitoring control PCM phase changes during the simulation. Note that these parts are not taken into account in the numerical model. A three-dimensional numerical model is considered to compare trends detected in the experimental study [1]. A constant heat flux is applied from the heat source to the heat sink bottom.

Table 1. Thermo-physical properties of each material

Material	Th. conductivity (W/mK)	Specific heat (kJ/kgK)	Latent heat (kJ/kg)	Solidification point ($^{\circ}\text{C}$)	Melting point ($^{\circ}\text{C}$)	Density (kg/m^3)
Aluminum	201	0.9	-	-	606.4	2700
Rubber pad	0.043	1.23	-	-	-	2500
Paraffin Wax	0.212 (s)	2.8	173.6	56	58	880 (s)
	0.167 (l)					790 (l)

The thermophysical properties of each material is presented in Table 1. To study the round pin-fin heat sink behavior fulfilled with PCM, a Finite Element (FE) computing software ANSYS is proposed. A uniform heat flux ($Q = 2800 \text{ W/m}^2$) is applied at the bottom of the heat sink.

The temperature-time profile is presented in Fig. 2 for a 3 mm pin-fin heat sink diameter. Note that black and blue curves correspond to numerical and experimental results respectively, throughout the charging phase under $Q = 2800 \text{ W/m}^2$.

For the charging phase, three zones can be distinguished: solid, liquid and latent heating region.

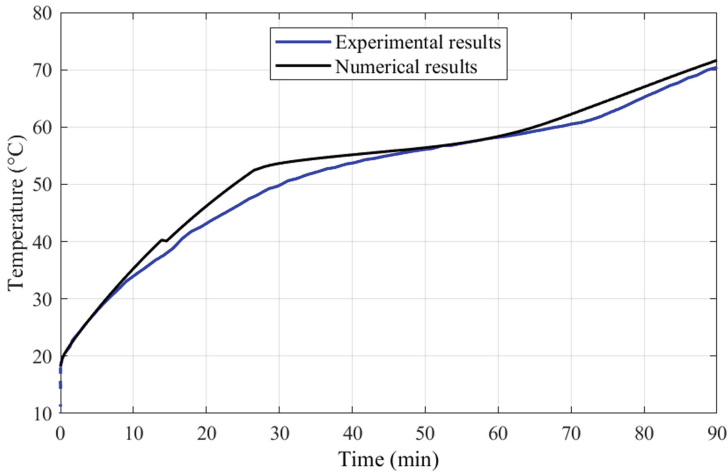


Fig. 2. Temperature-time profile for both experimental and numerical results $Q = 2800 \text{ W/m}^2$.

It can be seen that numerical results compare relatively well with the experimental data found by Arshad et al. [1]. Therefore, the parametric analysis can be then proceeded.

4 Parametric Analysis

4.1 PCM Selection

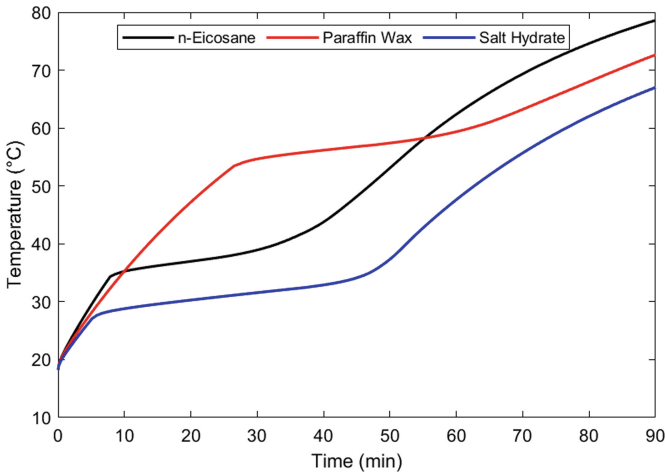
For the PCM-based heat sink cooling technology, the melting temperature is considered the most essential factor for PCM thermophysical properties. The thermophysical properties of each studied PCM material are presented in Table 2.

Figure 3 presents the temperature-time evolution measured at the bottom of the heat sink under a uniform heat flux $Q = 2800 \text{ W/m}^2$. In this figure, thermal energy performance is studied for n-Eicosane, paraffin wax and salt hydrate presented respectively by the black, red and blue curves.

Table 2. PCMs thermo-physical properties

Material	Th. conductivity (W/mK)	Specific heat (kJ/kgK)	Latent heat (kJ/kg)	Solidification point ($^{\circ}$ C)	Melting point ($^{\circ}$ C)	Density (kg/m ³)
Paraffin Wax	0.212 (s)	2.8	173.6	56	58	880 (s)
	0.167 (l)					790 (l)
n-Eicosane	0.39 (s)	1.9 (s)	237.4	35.5	36.5	810 (s)
	0.157 (l)	2.2 (l)				770 (l)
Salt hydrate	0.6	2	200	27	32	1500

It can be considered that salt hydrate is one of the best PCM material comparing with other PCMs. In fact, salt hydrate has the ability to store more thermal energy than other PCM benefiting from higher thermal conductivity as well as its higher density.

**Fig. 3.** Temperature-time profile for the studied PCMs.

At $t = 90$ min, it can be clearly seen that the maximum reached temperature for salt hydrate is about 67° C and it presents the lower temperature comparing with other ones. Then, salt hydrate will be taken as PCM for the following sections.

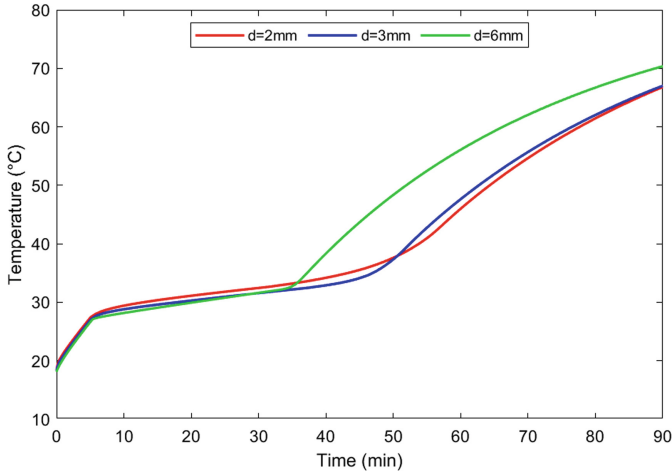


Fig. 4. Temperature-time evolution for each pin diameter variation.

4.2 Pin Diameter Variation

The configuration of the studied heat sink is a 11×12 round pin-finned matrix. Figure 4 shows the temperature-time profile for each pin-fin diameter. Noting that red, blue and green curves present the temperature evolution for $d = 2$ mm, $d = 3$ mm and $d = 6$ mm pin-fin diameter.

This study demonstrates that the configuration with a pin diameter of 2 mm presents the best thermal energy behavior in term of thermal energy storage as well as maximum reached temperature.

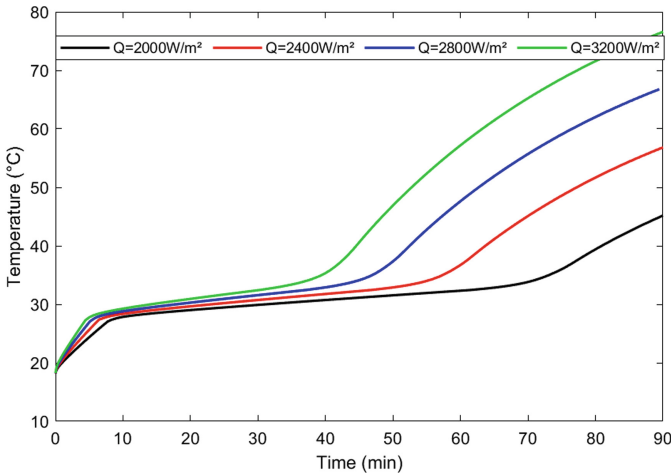


Fig. 5. Temperature-time evolution for different heat fluxes load.

4.3 Power Level Variation

The temperature-time profile history is presented in Fig. 5 for different heat loads: 2000, 2400, 2800 and 3200 W/m². It can be noted that salt hydrate is used as PCM. Referring to Fig. 4, it can be clearly seen that the latent heating phase, which is the period where PCM changes from the solid state to its melting, decreases when the heating power increases. For $Q = 2000$ W/m², PCM reaches its melting phase at $t = 75$ min but it ends within $t = 40$ min for a heat power about $Q = 3200$ W/m².

5 Adopted Parameters for the Studied Cooling System

The parametric analysis leads to investigate the thermal performance as well as to determine an optimal design which has the ability to give a minimal reached temperature for the charging phase. Several parameters are studied to give the best thermal energy management. In this study, a PCM-based 11 × 12 round pin-fin heat sink matrix is carried out. A parametric study shows that salt hydrate has the ability to store a high thermal energy comparing with n-Eicosane as well as paraffin wax. In addition, a heat sink with a 2 mm pin-fin diameter presents the optimal heat sink geometry.

6 Conclusion

In this study, a finite element simulation of a cooling system is carried out to quantify the thermal energy behavior of a PCM-based round pin-fin heat sink fulfilled with PCM. This study presents the impact of parameters (PCM selection, pin diameter and input heat flux) on thermal energy performance of the studied model. In fact, salt hydrate is considered as the best PCM which has the ability to store more thermal energy during the charging phase comparing to other PCMs (n-Eicosane and Paraffin Wax). Increasing the heat power level has the same effect on the maximum temperature measured at the end of charging phase. Otherwise, the latent heating phase, which is the period where PCM changes from the solid state to its melting, decreases when the heat power increases. Numerical results confirm the benefits of finite element simulations for passive cooling applications especially for PCM-based heat sink case. This study provides an optimal design and it presents an efficient thermal energy management. An experimental study is required to ameliorate the optimal obtained configuration and to determine all studied physical parameters of the optimal model.

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