Proceedings of Engineering and Technology Innovation, vol. 7, 2017, pp. 01 - 07

A Designed Enclosure Unit for Loop-Mediated Isothermal Amplification

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Received 17 July 2017; received in revised form 05 August 2017; accepted 25 August 2017

Abstract

The gene amplification technique is used in medical science and biotechnology popularly. The loop-mediated isothermal amplification (LAMP) is a nucleic acid amplification method that can be utilized in low-resource settings and does not require expensive or complex instruments. The annealing process of LAMP is performed at a constant temperature (around 65 ℃) for an hour. From previous works, phase change materials (PCMs) have been applied for the latent heat energy storages due to their isothermal operation during phase transitions. The utilization of the melting temperature of the paraffin wax to maintain the suitable temperature for LAMP process is introduced in our study. To enhance the heat transfer inside the energy storage unit, several pin fins are constructed on the inner surface of the unit which is 50 mm × 50 mm × 50 mm in inner size. The influence of various numbers of pin fins on the temperature distribution is examined by the numerical simulation. The heat transfer inside the paraffin enclosure with fins is better than that without fin. It can be found that the temperature uniformity in the PCM inside the enclosure with fins shows much better. Though the numbers of the fin are increased, some transfer energy from the heat source remains at the enclosure wall and cannot penetrate into the PCM. The duration for all PCM melted from solid phase to liquid phase is over 10 minutes. In the future, the geometric parameters on the duration for phase transition of PCM inside the LAMP chamber will be investigated**.**

Keywords: phase change materials, LAMP, paraffin wax

1. Introduction

The detection of nuclei-acid sequences is popularly used in medical research, biotechnology and food science. The Loop-mediated isothermal amplification (LAMP) is a biotechnique that can amplify deoxyribonucleic acid (DNA) within 60 minutes under isothermal conditions (50-65 ℃). This technique, a highly sensitive technique that can be used in low-resource settings and does not require expensive or complex instruments [1], is suitable for small-scale hospitals, primary care facilities and clinical laboratories in developing countries [2-3]. In previous studies, the LAMP technique was able to yield the amplification of 109-bp of DNA [4], and applied to detect the virus as follows: Mycobacterium [1], Tuberculosis [5], M. avium and M. intracellulare in sputum [3], Porcine kobuvirus [6], etc.

The LAMP process is to anneal DNA and primers with an appropriate constant temperature. To build a reaction device for LAMP process, one of the most important issues is to design a reaction chamber that can be kept at a constant temperature for a period of time. When heat energy is supplied to or extracted from a phase change material (PCM), there is only a little

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change of temperature inside the PCM. Therefore, PCM can be used to stabilize the temperature in an application for LAMP process. In general, PCM refers to solid-liquid phase changes only [7]. Paraffin wax is the most commonly used commercial organic PCM because of its high heat of fusion, varied phase change temperatures, negligible supercooling, lower vapor pressure in a melt and chemically inert and stable behavior [8].

However, due to low thermal conductivity of paraffin wax, it requires large surface area for heat exchange [9]. Kandasamy et al. [10] studied about using the paraffin wax as the PCM-based heat sink. The results from simulations and experiments have shown that PCM-based heat sink can be used in intermittent-use devices. Nayak et al. [11] improved the cooling of the electronics devices by using PCM with fins made of thermal conductivity enhancer material. Pakrouh et al. [12] presented a numerical investigation to optimize the geometry of PCM-based fin heat sinks. The result showed the fin height affects the base temperature. Hosseinizadeh et al. [13] carried out a comparison between heat sink with and without PCM. Their results revealed that fins thickness larger than 4 mm did not improve the performance of the heat sink. Kamkari et al. [14] demonstrated the experimental results of PCM melting in an enclosure with and without horizontal partial fins. Results indicated that when the surface-averaged Nusselt number was reduced, increasing the number of fins decreased the melting time and increased the total heat transfer rate.

LAMP has been utilized for the detection of DNA and/or RNA from a wide range of bacterial and viral pathogens [15-17]. Curtis et al. [15] presented a non-instrumented nucleic acid amplification (NINA) heating device. The heat from the exothermic chemical reaction was enough to anneal DNA sample for 60 minutes. However, the changing of the ambient temperature had an effect on the temperature stability during the amplification process and it was difficult to control the heat from the chemical reaction. In our LAMP device, a cartridge heater is utilized to generate heat energy for melting PCM and then the melting PCM is used for stabilizing the sample temperature during the DNA amplification. This process does not need any thermal controller and the integration of the LAMP device was easy.

2. Numerical Methodology

A schematic diagram of three-dimensional the enclosure physical model consist of lid, fin array and cavity, the DNA sample put on the top surface of the lid is shown in Fig. 1(a). Considering the symmetry of the geometry, only one quarter of the physical model is included for computation. The pin fin array and the cavity are made of aluminum which contains the PCM. A uniform heat power is applied at the bottom surface of the cavity. Initially, the solid PCM and enclosure are in thermal equilibrium with the ambient temperature, 20 ℃. The solid and liquid phases of PCM are homogeneous and isotropic. Thermal resistance across the wall of the container is neglected and lateral sides of the rectangular enclosure are well insulated. The melting point of PCM is 65 ℃. The effect of natural convection within the melt PCM is neglect because the space into enclosure is moderately narrow and fin array barrier velocity flow when phase transition to liquid. The PCM undergoes the transition from the solid state to the liquid state. There are governing equations as follows.

Heat conduction in liquid region:

$$\frac{\partial T_l}{\partial t} = \alpha_l \frac{\partial^2 T_l}{\partial x^2} + \alpha_l \frac{\partial^2 T_l}{\partial y^2} + \alpha_l \frac{\partial^2 T_l}{\partial z^2} \ , \ t > 0 \tag{1}$$

Heat conduction in solid region:

$$\frac{\partial T_s}{\partial t} = \alpha_s \frac{\partial^2 T_s}{\partial x^2} + \alpha_s \frac{\partial^2 T_s}{\partial y^2} + \alpha_s \frac{\partial^2 T_s}{\partial z^2} \ , \ t > 0 \tag{2}$$

Interface temperature:

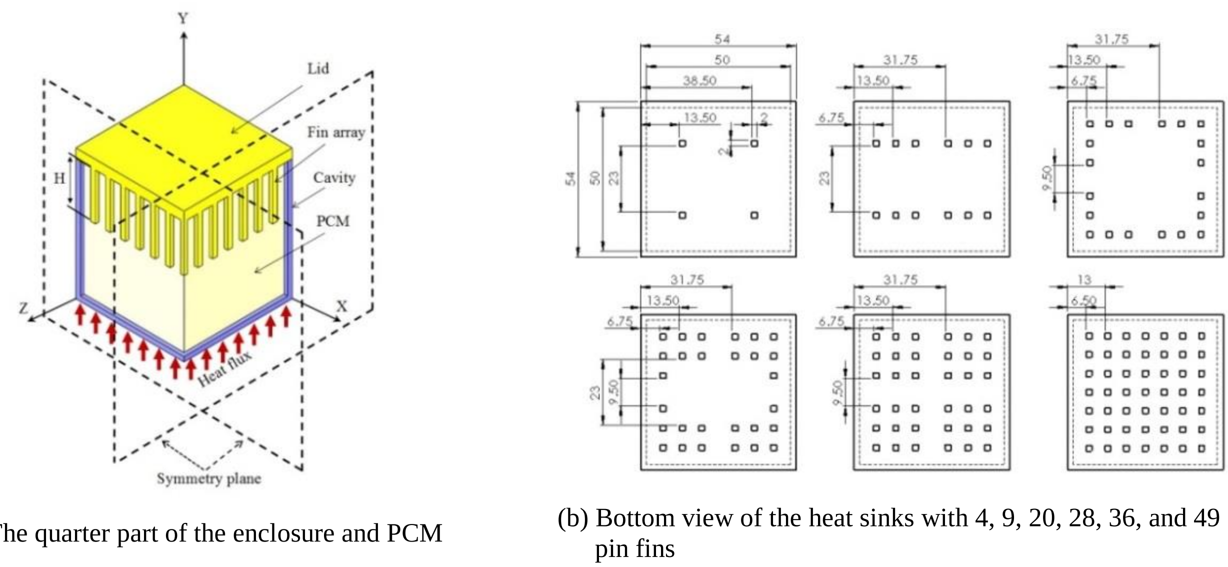
$$T(x, y, z, t) = T_m \tag{3}$$

Stefan condition:

$$k_s \frac{\partial T_s}{\partial x} - k_l \frac{\partial T_l}{\partial x} = H_f \rho \frac{dX}{dt}, t > 0 \quad (4)$$

where α is thermal diffusivity. k is the thermal conductivity. γ is the melt fraction during the phase change process and is defined by the following relations: $\gamma = 0$, if $T < T_s; \gamma = 0$, if $T > T_l$; $\gamma = \frac{T - T_s}{T_l - T_s}$, if $T_s < T < T_l$. T_m is melting temperature, the subscript l and s is liquid and solid phase respectively. A grid system is composed of 32768 to 61952 hexahedral cells, which depends on the numbers of fin. The numbers of fin are varied from 4 to 49 pin fins, H is fin height, which is varied from 20 mm to 47 mm and the fin maintains 2 mm thickness of whole models shown in Fig. 1(b). A constant heat power of 14 W is applied at the bottom surface of the enclosure.

A finite volume approach is adopted by using computational fluid dynamics (CFD) software ESI-CFD (V2006, CFD Research Corporation, Huntsville, AL, USA) to model the PCM melting process. A structured grid system with good orthogonality is recommended for accurate prediction and reliability. In this study the geometric model for the three dimensional rectangular structure is considered. In the computation of the enthalpy of the simulation model, the spatial discretizations are performed using a second-order upwind scheme. The conditions of convergence can be divided into two kinds. The first one is the maximum number of the solver iterations. The second one determines the convergence criteria to be used. In this study, we perform 100 sweep times and use 5×10-5 as the convergence criterion. Grid sensitivity is evaluated by using different element sizes to ensure that the simulated results are independent of element size. The element size is repeated until the similarity in results is within the acceptable solution tolerance (0.1%). This study use the PCM, which has the melt point near the amplification process of LAMP technique is the Rubitherm® RT64HC paraffin wax has a solid density of 880 kg/m^3, a liquid density of 780 kg/m^3, a specific heat of 2000 J/kg-K, a latent heat of 2.3×10^5 J/kg and a thermal conductivity of 0.2 W/m-K. Aluminum has a density of 2700 kg/m^3, a specific heat of 880 J/kg-K and a thermal conductivity of 190 W/m-K.



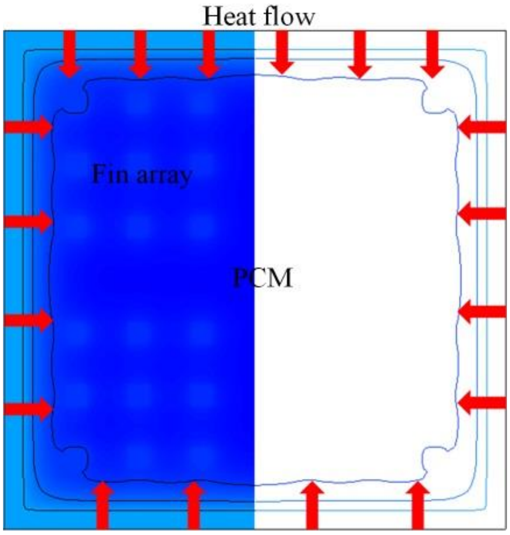
(a) The quarter part of the enclosure and PCM

(b) Bottom view of the heat sinks with 4, 9, 20, 28, 36, and 49 pin fins

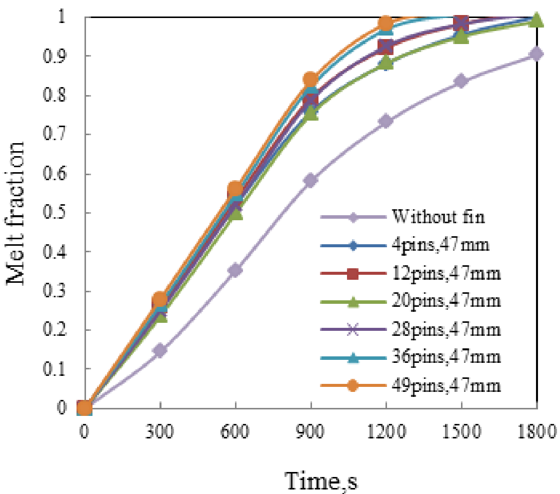
Fig. 1 The numerical models of 2 mm thickness fin

3. Results and Discussion

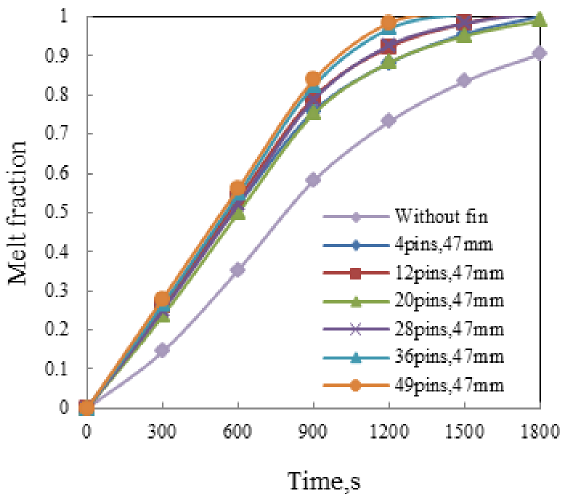
In this section, we present the thermal characteristics obtained from the three dimensional simulations and the results of the parametric studies are shown. The discussion concerns the calculated temperatures and melt fractions of the PCM as functions of time. In our study, heat conduction is the main heat transfer mechanism inside the enclosure. The heater generates heat flux is attached to the bottom of the aluminum enclosure with a high thermal conductivity. With an increase in time, the heat energy from pin fin array and cavity through to the solid PCM, melting of the PCM and then heating of the molten PCM to temperature above its melting point. The material of the fins is identical to the enclosure. Therefore the temperature of the enclosure and the fins increase more than that of PCM. The temperature of the lid might exceed the temperature suitable for amplification process in LAMP technique. The purpose of the fins is enhancing thermal conductivity of PCM that contain inside an enclosure, the heat flux flow with heat conduction from the heat source at the bottom cavity aluminum to PCM. The large disparity thermal conductivity between aluminum and PCM that make effect to the intensive heat flux flow in material. The fins array is proficiently constrained the temperature for annealing the sample on the top surface enclosure shown in Fig. 2(a). In order to assess the influence of fin, melt fraction with time variation is evaluated for the PCM with fins and without fin



(a) Temperature contour of 36 pin fins and fin height of 47 mm at top view at 110 s



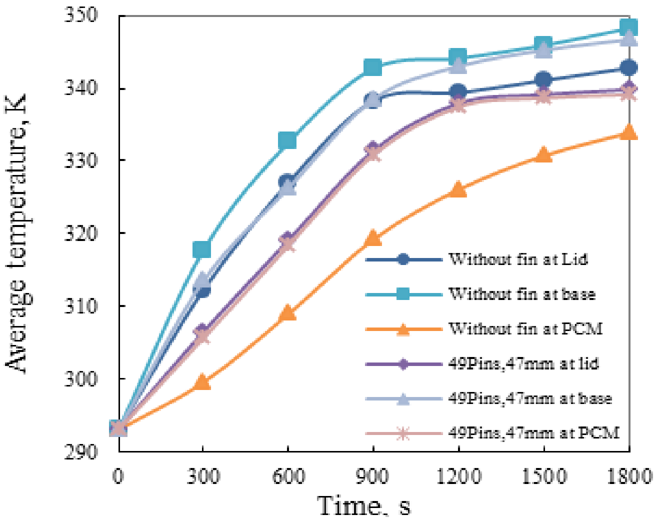
(b) Compared melting fraction varied



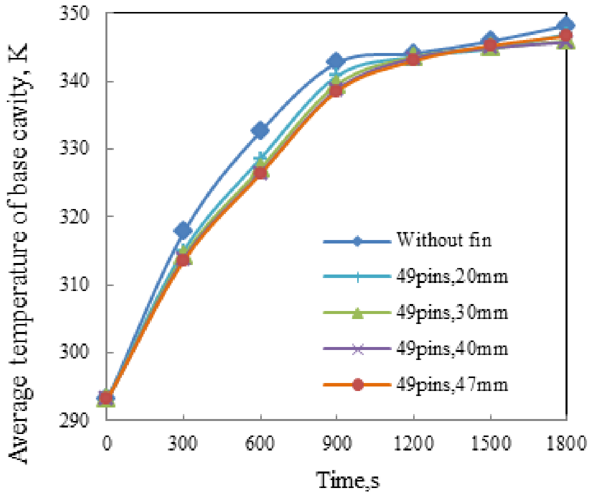
(c) Compared melting fraction varied fin height.

Fig. 2 The melt contour inside enclosure of PCM and Melt fraction effected of number of pin fin and fin height

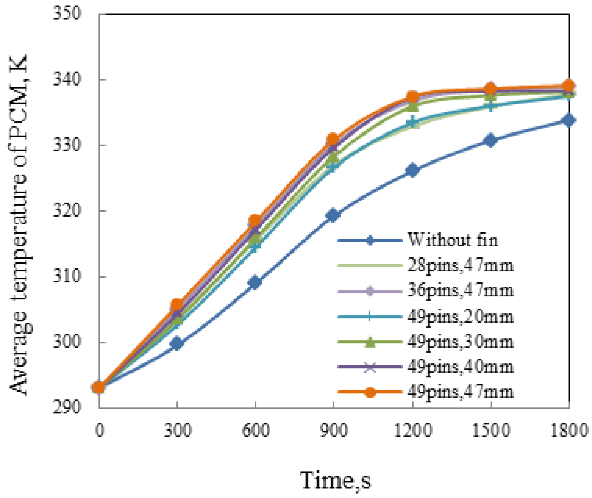
After 1800s, there are three cases of PCM no complete melting to liquid as follows: without fin, 20pins fin and 47mm fin height, and 49 pins fin and 20mm fin height Fig. 2(b) and 2(c) show the temporal variations of melt fractions during melting processes for finned enclosure and enclosure without fun. A rapid increase in temperature of PCM is observed with fins than that of PCM without fins. This is because the longitudinal finned material is able to transfer heat from the heat source quickly. The higher heat transfer rate was induced by the presence of fins near the heat source causes faster melting of PCM. Thus, the total melting time is reduced compared to the system without fins. The fins accelerate the heat transfer rate from the surface of heat source to and through the PCM. The melt fraction of PCM with 49 pin fins and fin height of 47 mm is higher than that of other cases. Regarding to the enclosure with 36 pin fins, the melt fraction is lower than that with 49 pin fins, but is almost the same. Therefore, the enclosure with 36 pin fins and fin height of 47 mm is capably performed as well.



(a) Compare without fin with 49 pin fins, 47 mm fin height



(b) At base cavity



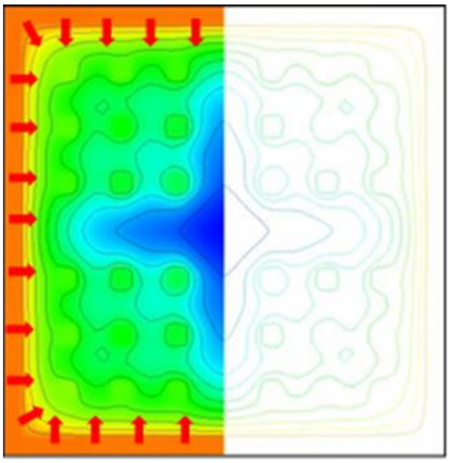
(c)PCM

Fig. 3 Average temperature profiles

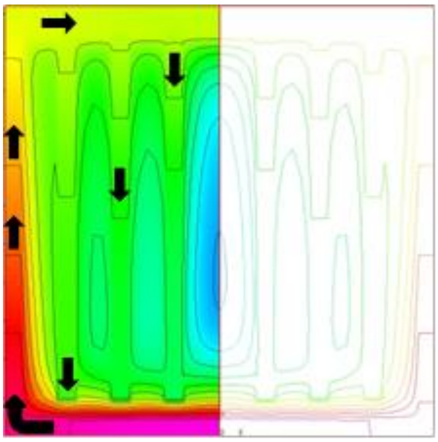
The gradients of the temperature contours are large at the bottom of the enclosure during the observed times because the applied heat source is at the bottom of the enclosure. The PCM has a low thermal conductivity. Therefore, the large heat flow along aluminum wall causes high temperature, the PCM temperature is improving almost lid temperature when applied fin array the 49 pins fin and 40mm fin height shown in Fig. 3(a). Although concentrated temperature at the base cavity in 49 pins and 40 mm fin height is most (neglect without fin case) Fig. 3(b), the temperature profiles of PCM almost 49 pins and 47 mm fin height case after 900s. The solid PCM was heated by the adjacent liquid PCM. Hence fin array enhanced and increased the melting rate. The extended surfaces of the fin array are inserted into PCM and lead to more heat transfer than the enclosure without fin, as shown in Fig. 3(c).

The fin array and cavity structures cause the heat energy penetrated into the PCM. The largely different thermal conductivity between aluminum and PCM has the effect to intensive gradient temperature occur on surface heat transfer of aluminum, demonstrated in Fig. 4(a,b), and the space without fin remain solid state indicate that the heat transfer between liquid to solid not well. The melting rate is enhanced by pin fin array. The number of pin fin and fin height directly influence the surface heat transfer. When the surface heat transfer is increased, the heat energy for phase transition is reduced in Fig. 4(c). It is because the large heat flux through surface fin to PCM change to complete the melting, the liquid PCM cannot absorb energy. The influence of various fin heights and numbers of pin fin on melt fraction when each fin surface heat transfer is almost equal is shown in Fig. 4(c). The surface heat transfer are 22840 mm^2 with 49 pin fins and 20 mm fin height, 22528 mm^2

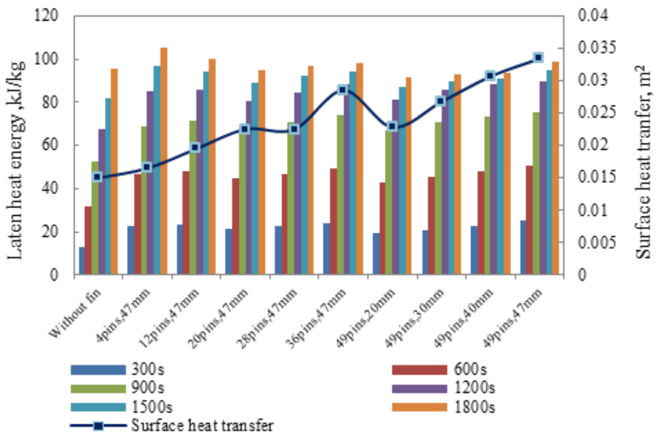
with 28 pin fins and 47 mm fin height and 22520 mm^2 with 20 pin fins and 47 mm fin height, respectively. The 49 pin fins and 40 mm fin height has surface heat transfer 30680 mm^2 less surface heat transfer than 49 pin fins and 47 mm fin height (33424 mm^2) and use latent heat energy for phase transition. The difference of the melt fractions among these cases are within 10% after the beginning of the duration of 300 s. Therefore, the latent heat energy storage depends on the surface of the heat transfer. The saved energy for each model can be found by integrating the area under the relative latent heat energy and time. The slope of each graph indicates the energy to be used within 1800s. The group of 49 pin fins saves more energy than others with large space between adjacent fins.



(a)Top view cross-section at half of fin length

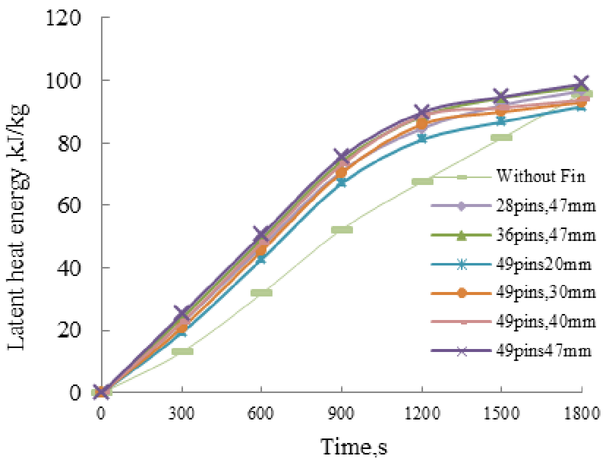


(b) Front view cross-section at middle of first row of fin

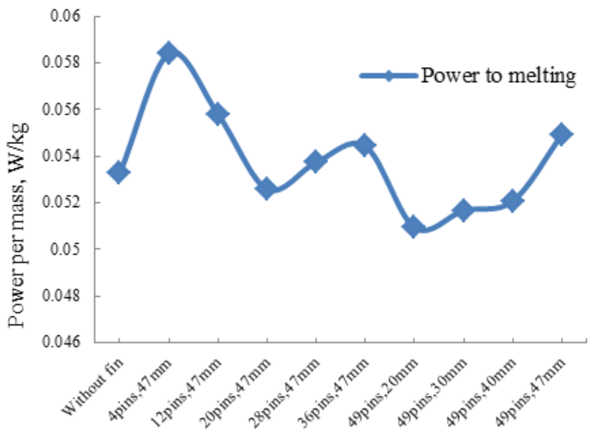


(c) Latent heat energy and surface heat transfer

Fig. 4 Temperature contours of 36pin 47mm fin height model at 300



(a) The area under each the graph



(b) The slope value each graph of latent heat energy

Fig. 5 The latent energy in each case used to melt PCM in 1800s

4. Conclusion

In this paper, the numerical study of the designed PCM enclosure for LAMP was presented. The transient simulation of heat conduct problem of an enclosure with PCM is shown with several pin fins inside the enclosure. The main parameters about enhancing the heat transfer were the number of pin fin and the fin height. The simulation results show an enhancement of melting rate and a decreasing temperature gradient near the heating wall of enclosure with fin array extended from lid. The thorough pin fin position distribution and the number of pin fin can be used to save the energy to melt PCM. The simulation study shows the pin fin array technique can improve the potential of PCM for applying in the LAMP machine.

Acknowledgment

The authors would like to thank the Ministry of Science and Technology of the Republic of China for financially supporting this research under Contract No. MOST 105-2313-B-020-007-.

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