Thermal network calculation model for phase change material with SPICE circuit simulator

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Abstract
The SPICE model of phase change material (PCM) for thermal network transient calculation was investigated. The nonlinear behavior of PCM due to latent heat was modeled by using the voltage dependent current source and the capacitor. A latent heat is stored in the capacitor as electric charges. Corresponding to the PCM phase state, such as solid, liquid and mixed phases, the dependent current source is controlled with PCM temperature and the latent heat quantity of PCM. Since the melting point of PCM has a distribution, the model in which multiple PCM models having different melting points and capacitor capacities were connected in parallel was employed. To validate the numerical simulation model, the aluminum case with PCM sealed inside was prepared. The sample was heated with a rubber heater from the bottom with different heat quantities. The temperature changes of the upper and lower surfaces were measured with thermocouples. The results showed the error between simulated and measured values were below ±4 °C and the calculation time took below real-time. This simulation model can be applied to cooling system optimization and temperature control system.

Keywords: Phase change material, Thermal design, Thermal network method, Temperature transient, SPICE model

1. Introduction

A cooling design of electronics has been getting harder due to the increased package density of electric devices and systems. An efficient device temperature control has been required to operate below the device temperature limitation. To cover to peak thermal load, maximum cooling capacity exceeding normal operating power is installed. One of the candidate solutions is to employ phase change material (PCM) for cooling systems. It helps device temperature becomes stable near the phase change temperature. Skach et al. were reported the thermal time shifting with a PCM can be used to reduce peak cooling load by up to 12 percent or increase the number of servers by up to 14.6 percent without increasing the cooling load (Skach et al., 2017). Furthermore, since it is difficult to use fans in mobile device cooling systems, applications of PCM has been studied (Moore et al., 2016 and Shao et al., 2014).

It is required to optimize the cooling system for electric devices, the thermal properties such as melting point and the volume of PCM according to the dynamically changing thermal workload. A computational fluid dynamics (CFD) calculation is generally used for thermal analysis. However, a temperature transient calculation of a device and system with a PCM takes long time using a typical CFD simulation. On the other hand, as a practical method of thermal analysis, thermal network calculation method has been studied. A thermal network calculation not only reduces the analysis time compared to CFD calculation, but also enables the analysis using the same circuit simulator as the electric circuit, thus enabling the coupled analysis of thermal and electricity elements. SPICE is used to provide a reasonably detailed analysis of circuits. And it is commonly used to circuit simulation. Hatakeyama et al. studied PCM model using thermal network method (Hatakeyama et al., 2011). The non-linearity of PCM was calculated with the Runge-Kutta method. In other thermal network model, PCM model with changing capacitance of the capacitor depend on the PCM temperature was
studied (Stupar et al., 2012 and Alawadhi et al., 2003). However, since PCM has nonlinear characteristics, a SPICE model of PCM has not been proposed. In this study, the thermal transient calculation of a device with PCM using SPICE circuit simulator that can be calculated with high accuracy in less than real time was investigated.

2. Nomenclature

| Symbol      | Description                         |
|-------------|-------------------------------------|
| A           | Area [m²]                           |
| C           | Capacitance [A·s/V], [F]            |
| Cₚₚ㎝       | Specific heat [J/(kg·K)]            |
| Cₛₚ㎝       | PCM capacitance [A·s/V], [F]        |
| Rₚₚ㎝       | Thermal capacitance of PCM [J/K]    |
| Rₚₚ㎝       | Thermal capacitance [J/K]           |
| D           | Experimental constant of natural convection [-] |
| L           | Reference length [m]                |
| Lₜ         | Latent heat of fusion [J/kg]        |
| I           | Current [A]                         |
| P           | Heat flow [W]                       |
| Pₛₚ㎝       | Heat flow to PCM as latent heat [W] |
| Q           | Charge [C]                          |
| Qₛₚ㎝       | Latent heat quantity of PCM [J]     |
| Qₚₚ㎝       | Heat quantity [J]                   |

Subscripts:
- liq : Liquid phase
- max : Maximum
- min : Minimum
- sol : Solid phase

3. Thermal modeling using thermal equivalent circuit model

The thermal-electrical analogy is a method of representing a thermal system by an analogous electrical system. Table 1 shows the analogy between thermal and electric model. In the thermal network method, each element is divided and connected two- or three-dimensionally as in the finite element method, so that elements having various shapes and different material characteristics can be modeled and calculated.

| Thermal model       | Electrical model       |
|---------------------|------------------------|
| Temperature         | Voltage                |
| Heat flow           | Current                |
| Thermal resistance  | Resistance             |
| Thermal capacitance | Capacitance            |
| Heat quantity       | Electric charge        |

Figure 1 shows a general two-dimensional thermal network model. This figure shows a general two-dimensional 2×2 block model (Stupar et al., 2012 and Wang et al., 2004). Where the resistance and capacitance are corresponded to thermal resistance and thermal capacitance, respectively. When divided into n×m blocks, the heat capacity is divided into n×m parts. From the viewpoint of the symmetry due to the heat flow of each block, the thermal resistance value is divided into 2n and 2m in each direction, respectively.
Since the generated heat in the electric device is diffused to atmosphere, the ground voltage in the electrical model was defined to ambient temperature. Therefore, all voltages as temperatures at each point were calculated with SPICE circuit simulator using the difference temperature from the ambient temperature. The temperatures at each point were obtained by adding the ambient temperature to the calculation result.

3.1 Target model of thermal analysis to be developed

The purpose of developing a SPICE model including PCM in this study is to optimize the cooling of electrical equipment, such as reducing the electric power consumption of cooling and controlling the package temperature under the system limitation. Aparaffin wax, which is generally studied for cooling electronic devices (Hatakeyama et al., 2011, Stupar et al., 2012 and Alawadhi et al., 2003), was used for PCM. However, for practical use, an optimization design is required for each system. The target thermal model is a structure in which a paraffin wax is placed on a heat sink for cooling electric equipment.

Figure 2 shows the outline of target cooling structure including PCM. Cooling for LSIs or power devices mounted on printed circuit boards is the target system in this study. A paraffin wax changes between a solid phase and a liquid phase near its melting point. It causes exothermic and endothermic reactions due to latent heat. Since the proposed PCM model expresses a wide range of material properties, it is necessary to be able to arbitrarily set the phase change temperature and latent heat.

3.2 Phase change material model

The proposed SPICE model of PCM is shown in Fig. 3. It was consisted of voltage dependent current source, resistors and capacitors. The proposed SPICE model of PCM was divided into four equivalent thermal resistance $R_{pcm}$ with a thermal capacitance $C_{pcm, in}$. The thermal resistances of PCM $R_{pcm}$ is defined as $R_{pcm} \sim R_{pcm, 4}$ corresponding to the heat flow $P_1 \sim P_4$ flowing from each node. The thermal capacitance $C_{pcm, in}$ is corresponded to heat capacity of PCM. The dependent current source was connected to the center node. And another capacitor $C_{pcm}$ is connected to the other side of dependent current source. The amount of charge stored in the capacitor $C_{pcm}$ is defined as latent heat quantity $Q_{pcm}$. 
A PCM have three different states, such as solid phase, liquid phase and mixed phase of solid and liquid phases. These three states can be expressed by controlling the current of dependent current source as depend on PCM temperature $T_{pcm,in}$ and latent heat quantity $Q_{pcm}$. When the PCM temperature exceeds the melting point, the heat flow to PCM $P_{pcm}$ is stored as latent heat. The maximum latent heat quantity of PCM is depending on the properties and volume of PCM. It is defined as $Q_{pcm,max}$. The charge of capacitor $Q_{pcm}$ is related to the voltage $V_{pcm}$ and capacitance of the PCM capacitor $C_{pcm}$ in Eq. (1). In this SPICE simulation, the voltages $V_{pcm}$ of PCM capacitor $C_{pcm}$ were used for comparison between the latent heat quantity $Q_{pcm}$ and the maximum latent heat quantity $Q_{pcm,max}$:

$$Q_{pcm} = C_{pcm}V_{pcm}$$  \hspace{1cm} (1)

When the PCM is divided into $n\times m$ block for analysis, the PCM capacitor $C_{pcm}$ of each block becomes $1/(n\times m)$. Among the changes in physical properties of PCM due to phase changes, factors other than latent heat that should be introduced into the model were investigated. It has been reported that density, specific heat, and thermal conductivity change due to phase change (Murali et al., 2011, He et al., 2004 and Sarı et al., 2007). The thermal conductivity is a large change of 50% or more in the papers. On the other hand, other properties of PCM are not significantly changed with phase. Therefore, the temperature dependent of thermal resistance change of PCM should be modeled in this study.

The detail of the state control will show the following.

### 3.2.1 Solid phase of PCM

When PCM temperature below the melting point $T_{pcm,melt}$, PCM is solid phase. PCM behaves the linear material, and can be modeled with thermal resistance and capacitance. And the latent heat quantity $Q_{pcm}$ is zero. As a material property of PCM, latent heat does not appear during PCM temperature below the melting point. However, in the simulation model, it is possible to take a state in which $C_{pcm}$ has charge with the temperature below the melting point. Therefore, it is strictly defined as described above. Since there is no latent heat effect under that condition, the heat flow $P_{pcm}$ charged in the capacitor $C_{pcm}$ is zero. The conditional expression for dependent current source is as follows:

If $T_{pcm,in} < T_{pcm,melt}$ and $Q_{pcm} \leq 0$
then $P_{pcm} = 0$

The thermal resistance of PCM in solid phase is defined as $R_{pcm,sol}$.

### 3.2.2 Liquid phase of PCM

When all of the PCM is melted, PCM becomes liquid phase. PCM behaves the linear material, and also can be modeled with thermal resistance and capacitance. In the liquid phase, PCM temperature $T_{pcm,in}$ is above the melting point of PCM $T_{pcm,melt}$. And the latent heat quantity $Q_{pcm}$ is above the maximum latent heat quantity of PCM $Q_{pcm,max}$. Since there is no latent heat effect in that condition, the heat flow $P_{pcm}$ charged in the capacitor $C_{pcm}$ is zero. The conditional expression for dependent current source is as follows:

If $T_{pcm,in} > T_{pcm,melt}$ and $Q_{pcm} > Q_{pcm,max}$
then $P_{pcm} = 0$
The thermal resistance of PCM in liquid phase is defined as $R_{pcm, liq}$.

### 3.2.3 Mixed phase of solid phase and liquid phase of PCM

When PCM temperature is near the melting point, PCM becomes mixed phase of solid and liquid phases. A heat is released or absorbed with latent heat behavior of PCM. Therefore, PCM temperature can be kept in near the melting point temperature in the mixed phase. Where, the direction of the current flowing into the node $T_{pcm, in}$ is defined as positive. When each heat flow into the node $T_{pcm, in}$ is defined as $P_i$, the sum of heat flow $P_{pcm}$ is defined as follows.

$$P_{pcm} = \sum_{i=1}^{4} P_i \quad (2)$$

In this thermal network model, when the PCM is in the mixed phase, the capacitor $C_{pcm}$ is charged with the sum of heat flow $P_{pcm}$ flowing into the node $T_{pcm, in}$. Therefore, the PCM temperature in $T_{pcm, in}$ is keep the same temperature during this feedback control about the dependent current source. The sum of heat flow is positive the PCM capacitor is charged until the charge of the capacitor $Q_{pcm}$ become maximum latent heat quantity $Q_{pcm, max}$. This operation is expressed to heat storage behavior.

On the other hand, the sum of heat flow $P_{pcm}$ is negative the capacitor $C_{pcm}$ is discharged to the main circuits until the charge of the capacitor $Q_{pcm}$ become zero. Since the mixed phase is a condition other than the solid phase or the liquid phase, the conditional expression for dependent current source is as follows:

If \( \{(T_{pcm, in} < T_{pcm, melt}) \text{ and } (Q_{pcm} \leq 0)\} \text{ or } \{(T_{pcm, in} > T_{pcm, melt}) \text{ and } (Q_{pcm} > Q_{pcm, max})\} \) then \( P_{pcm} = \sum_{i=1}^{4} P_i \)

Where, the bar above the conditional expression represents NOT in Boolean algebra. Thermal resistance of PCM $R_{pcm}$ is varied with the PCM temperate $T_{pcm, in}$ in this model. As described above, the thermal resistance of PCM is defined by a model that changes depending on the state. However, since the calculation may not converge if the thermal resistance is defined non-continuously to the temperature, a model that continuously changes the thermal resistance as shown in Fig. 4 was used in the mixed phase. The threshold temperate $T_{pcm, melt, min}$ and $T_{pcm, melt, max}$ were defined, and the model in which the thermal resistance changes linearly between them is defined in Eq. (3).

![Fig. 4 Thermal resistance change model with temperature](image)

$$R_{pcm} = \begin{cases} R_{pcm, sol} & (T_{pcm} < T_{pcm, melt, min}) \\ aT_{pcm, in} + b & (T_{pcm, melt, min} \leq T_{pcm} \leq T_{pcm, melt, max}) \\ R_{pcm, liq} & (T_{pcm} > T_{pcm, melt, max}) \end{cases} \quad (3)$$

$$a = \frac{R_{pcm, liq} - R_{pcm, sol}}{T_{pcm, melt, max} - T_{pcm, melt, min}}$$

$$b = \frac{T_{pcm, melt, max}R_{pcm, sol} - T_{pcm, melt, min}R_{pcm, liq}}{T_{pcm, melt, max} - T_{pcm, melt, min}}$$
Table 2 SPICE model condition table for each phase

| Phase          | Solid phase          | Mixed phase          | Liquid phase         |
|----------------|----------------------|----------------------|----------------------|
| Circuit diagram|                      |                      |                      |
|                | $T_{pcm, in}$         | $T_{pcm, in}$         | $T_{pcm, in}$         |
|                | $R_{pcm2, sol}$       | $R_{pcm3, sol}$       | $R_{pcm2, liq}$      |
|                | $R_{pcm1, sol}$       | $R_{pcm3}$            | $R_{pcm3, liq}$      |
|                | $C_{pcm}$             | $C_{pcm}$             | $C_{pcm}$            |
|                | $Q_{pcm} = 0$         | $P_{pcm} = 0$         | $P_{pcm} = 0$        |
|                |                      | $P_{pcm} = \sum_{i=1}^{4} P_{i}$ | $R_{pcm, liq} \leq R_{pcm} \leq R_{pcm, sol}$ |
|                |                      | $R_{pcm, liq} \leq R_{pcm} \leq R_{pcm, sol}$ | $R_{pcm} = R_{pcm, liq}$ |

Conditional expression

- $(T_{pcm, in} < T_{pcm, max}) \& (Q_{pcm} \leq 0)$
- $((T_{pcm, in} < T_{pcm, melt}) \& (Q_{pcm} \leq 0)) \lor ((T_{pcm, in} > T_{pcm, melt}) \& (Q_{pcm} > Q_{pcm, max}))$
- $(T_{pcm, in} > T_{pcm, melt}) \& (Q_{pcm} > Q_{pcm, max})$

Current

- $P_{pcm} = 0$
- $P_{pcm} = \sum_{i=1}^{4} P_{i}$
- $P_{pcm} = 0$

Thermal resistance

- $R_{pcm} = R_{pcm, sol}$
- $R_{pcm, liq} \leq R_{pcm} \leq R_{pcm, sol}$
- $R_{pcm} = R_{pcm, liq}$

Table 2 shows the SPICE model condition table for each phase that summarizes the above. Since no latent heat is generated in the solid phase and liquid phase, the current of the dependent current source becomes zero. Only thermal resistance is different between solid and liquid phases. In the mixed phase, the dependent current source charges the capacitor with all the flowing current. This phase is defined as a phase that is neither solid nor liquid. In this SPICE model, the dependent current source is controlled as follows by inverting the above conditional expression.

If $\{(T_{pcm, in} < T_{pcm, melt}) \land (Q_{pcm} \leq 0)\} \lor \{(T_{pcm, in} > T_{pcm, melt}) \land (Q_{pcm} > Q_{pcm, max})\}$

then $P_{pcm} = 0$

else $P_{pcm} = \sum_{i=1}^{4} P_{i}$

In the SPICE calculation of this model, the minimum calculation step is set to 100 msec., which is sufficiently smaller than the thermal time constant of PCM, which is the product of the thermal resistance and the thermal capacity of the PCM model. Moreover, even if the calculation step was shortened further, the calculation result was not affected.

### 3.2.4 Phase change temperature deviation model of PCM

In the above-thermal model, it is a model that changes rapidly with the melting point of PCM. However, since PCM such as paraffin wax is not a pure substance, the phase change temperature has a distribution. Assuming that the temperature distribution of the melting point is a Gaussian distribution (Murai et al., 2015, He et al., 2004 and San et al., 2007), the full width at half maximum (FWHM) is defined as shown in Fig. 5. Where, $T_{pcm, melt, min}$ is defined below the half width at half maximum of melting point $T_{pcm, melt}$ and $T_{pcm, melt, max}$ is defined above. Since the total latent heat of PCM is $Q_{pcm, max}$, each maximum latent heat amount for each PCM melting point was modeled as $Q_{pcm, max}/4$, $Q_{pcm, max}/2$, $Q_{pcm, max}/4$, respectively.

In order to express this phenomenon, a model in which the above three models having different melting points and capacitor capacities are connected in parallel was employed. These models can adjust the amount of dispersion according to the physical values of PCM by the number of melting point steps and capacitor capacitance distribution.
4. Experimental procedure for numerical simulation verification

To validate the developed simulation model, the aluminum case with PCM sealed inside was prepared. The external size had been set in consideration of the heat sink used in typical servers. Regarding the thickness of the PCM, we decided to make the maximum loading amount within that size as a basic study of the model. The dimensions of the aluminum case were 50 mm length, 50 mm wide, and 25 mm height. The aluminum material was A5052P. In order to simplify the analysis model, the aluminum surface was mirror-polished to create samples and models that minimized the effects of radiation. Therefore, the model did not calculate thermal radiation in this study. The aluminum case was filled with $19 \times 10^{-6}$ m$^3$ of a commercially available PCM having a melting point of 57 °C (330 K). Schematic of fabricated sample was shown in Fig. 7. There was the space above the PCM due to the volume change during the phase change. This space was modeled as the thermal resistance of air. However, the volume change of PCM was not modeled in this study.
Where, three degrees below the melting point $T_{pcm, melt}$ was defined as $T_{pcm, melt_{-min}}$, and three degrees above was defined as $T_{pcm, melt_{-max}}$. The sample was heated from the bottom with a rubber heater of the same area on the bottom of the sample. A polyurethane foam was placed between the bottom of the heater and the base. The fabricated aluminum case was located free space on the top and side surfaces during measurement. And the room temperature was 26 °C (299 K). The temperature changes of the upper and lower surfaces of aluminum case were measured with thermocouples. The heater power was changed to 4, 6, and 8 W. In these experiments, the lower part of the sample was heated to 80 °C (353 K), and then the heating was stopped and the sample was cooled. In the 4 W sample, since the temperature did not rise to 80 °C (353 K), the heater was stopped in a thermal equilibrium state.

The natural convection on the top and side of the sample was modeled as follows in this analysis. Thermal resistance by natural convection is calculated with the following equation. Where $\alpha$ is heat transfer coefficient, and $A$ is the area of surface.

$$R_{conv} = \frac{1}{\alpha A}$$

(4)

The heat transfer coefficient is obtained following equation.

$$\alpha = 2.51D \left( \frac{\Delta T}{L} \right)^{0.25} = 2.51D \left( \frac{T - T_{amb}}{L} \right)^{0.25}$$

(5)

Where, $D$ is experimental constant determined by top and side of sample, $L$ is the characteristic length, $\Delta T$ is the temperature difference between the object and the ambient temperature $T_{amb}$. In this study, the values of 1.3 and 1.4 were used for experimental constant $D$ on the top surface and the side surface, respectively. In order to simplify the calculation, the model was a first-order approximation in the analysis temperature range of 25 (298) to 80 °C (353 K). A voltage dependent resistor model was used.

Since the shape of the fabricated sample was a square in the horizontal direction, the calculation model is not a three-dimensional calculation but a two-dimensional model. The PCM part was divided into 3 parts in the vertical direction and 5 parts in the horizontal direction. This vertical layer structure models that PCM gradually changes phase in layer structure. Although it was also examined that it was vertically divided into 5, the analysis results showed no change, so it was divided into 3 in this study. Figure 8 shows the developed SPICE model for validation. The material properties of used paraffin and aluminum is shown in Table 3.

| Table 3 Properties of the PCM and Aluminum (A5052P) |
|-----------------------------------------------|
| $\rho$ [kg/m$^3$] | $C_p$ [J/(kg·K)] | $\lambda$ [W/(m·K)] | $L_a$ [kJ/kg] | $T_{pcm, melt}$ [K] |
|-----------------|-----------------|-----------------|--------------|-----------------|
| Paraffin (solid) | 920 | 1970 | 0.4 | 145 | 313-343 |
| Paraffin (liquid) | 750 | 2180 | 0.2 | - | - |
| Aluminum (A5052P) | 2680 | 880 | 140 | - | - |
6. Numerical Results and Discussion

Figure 9 shows a comparison of the measured and calculated temperatures for the top surface and bottom of the fabricated sample at an applied power of 4 W, 6 W, and 8 W. Where, the temperature of top surface center of the aluminum case was shown as surface, and the temperature between the aluminum case and the rubber heater is shown as bottom. Using a Core i5-3340M 2.7 GHz processor, the calculation time required for transient response analysis of 6000 seconds was about 60 seconds. The calculation time was about 1/100 of the desired transient response analysis time. Due to the absorption of latent heat when melting PCM at temperatures near the melting point, suppression of temperature rise was observed in both measurement and experimental results. It was confirmed that the time during which the temperature rise is suppressed increases as the amount of heat applied increases. There is also a good agreement between these measured and calculated values. The error between them is ± 4 °C or less, which is considered to be sufficiently accurate in the cooling optimization analysis of the equipment. The estimation error tends to increase as the amount of heat applied increases. In this study, PCM convection was not modeled. When PCM is in the solid state, there is no mass transfer, so it is not affected by convection. However, it seems that internal convection occurs in the mixed phase and liquid phase where liquid is generated. The increase in the error in the mixed phase and the liquid phase was observed in comparison with the experiment, but the effect seems to be small in this experiment.

Figure 10 shows the central block PCM temperature for each layer and the top surface and bottom temperatures of the aluminum case calculated. In the state in which the PCM phase has not changed, the PCM temperature was almost the same as the surface temperature of the aluminum case. However, when PCM became a mixed phase of solid and liquid, the PCM temperature was maintained at each melting point due to the endothermic and exothermic reactions of PCM, and then the PCM temperature rose when the maximum latent heat of PCM was exceeded. Due to this behavior, there were the differences in the PCM temperature and the aluminum case bottom temperature. Focusing on this point, a three-step flat region near the melting point was observed. This shows the behavior of the three-stage melting point model defined in the model. It can be confirmed that the flat region became shortened by increasing the amount of applied heat, and the dissolution rate was changed. Each step interval at a constant temperature does not depend on the amount of heat stored at each melting point. It indicates the difficulty of designing cooling equipment including PCM.

After the heating of the heater is terminated, it is considered that the temperature of the surface and the bottom will be the same because there is no heat flow between the heater and the bottom of the aluminum case. At this time, since the thermal time constant of PCM is larger than that of aluminum, there is a temperature difference inside the phase change between the part in contact with aluminum and the part far from aluminum.

Figure 11 shows the calculated latent heat of the PCM and the central block PCM temperature. The left axis of the graph shows the amount of latent heat, and the right axis shows the temperature of the PCM at that time. The green line, blue line, and light blue line indicate the lower, middle, and upper PCM layers, respectively. Among these, the thin line, the thick line, and the dotted line indicate the latent heat amount of lower melting point, center melting point, and higher melting point of PCM, respectively. Therefore, the latent heat quantity of the center melting point (thick line) shows the time change of the endothermic and exothermic reactions up to the maximum latent heat quantity of 70 J, which is half
of the maximum latent heat quantity of PCM divided into 15 blocks. The lower melting point (thin line) and the higher melting point (dotted line) show the time changes of the endothermic and exothermic reactions up to the maximum latent heat amount of 35 J, which is half of the maximum latent heat amount of center melting point. It shows the relationship between the change of latent heat quantity for each melting point of PCM and the stepwise change of PCM temperature. It was confirmed that the PCM temperature was maintained while the latent heat was generated at each melting point of each layer. The analysis result with an applied heat flow of 8 W shows the latent heat quantity of higher melting point of top PCM layer doesn’t reach the upper limit. It indicates that the third PCM layer was not completely melted. In this experiment, the aluminum case was heated from the bottom. Therefore, it was shown that in the temperature behavior of PCM when the temperature rose, when the amount of heat applied was small, PCM melts in order from the low melting point regardless of the layer. On the other hand, when the amount of heat applied increases, the internal temperature distribution of the PCM increases, which indicates that the lower melting part of PCM in the lower layer melts before the lower melting part of PCM in the upper layer. In the cooling process, it can be confirmed that the upper layer has exothermic reaction earlier than the intermediate layer, and there was also a heat dissipation from the upper surface. The developed model can estimate not only the temperature but also the transient of the latent heat inside the PCM. Thus, this model can be a very useful tool for cooling system optimization.

![Fig. 9 Comparison between measured and calculated temperature](image-url)
Fig. 10 Calculated PCM temperature

Fig. 11 Calculated latent heat quantity of PCM
7. Summary

The modeling of PCM by thermal network method using SPICE was studied. The nonlinear behavior of PCM due to latent heat was modeled by using dependent current source and capacitor. By controlling the amount of current of the dependent current source, the behavior of PCM according to three phase changes, such as solid phase, liquid phase, and mixed phase, are modeled. The change in resistance due to phase change was also modeled. Since general PCM has a distribution of melting points, the above PCM model is expressed by connecting three models with different melting points and latent heat amounts in parallel. The aluminum case containing PCM was fabricated, and the measured and calculated values were validated. The error between them below ±4 °C. The transient calculations were finished below real time. The developed model can be employed to design optimization for cooling. And also, it is expected to be applied to a temperature prediction for active temperature control for cooling system.

References

Esam M. Alawadi and Cristina H. Amon, PCM Thermal Control Unit for Portable Electronic Devices: Experimental and Numerical Studies, IEEE Transactions on Components and Packaging Technologies, Vol. 26 No. 1(2003), pp. 116-125.

Hatakeyama, T., Ishizuka, M., Takakuwa, S., Nakagawa, S and Tagahi, K., Experimental and Thermal Network Study on the Performance of a Pins Studded Phase Change Material in Electronic Device Cooling, Journal of Thermal Science and Technology, Vol.6, No.1, (2011), DOI: 10.1299/jtst.6.164

He, B., Martin, V., and Setterwall, F., Phase transition temperature ranges and storage density of paraffin wax phase change materials, Energy 29 (2004), pp. 1785–1804.

Murali, G., Mayulsamy, K., and Arjunan, T. V., An Experimental Study of PCM-Incorporated Thermosyphon Solar Water Heating System, International Journal of Green Energy (2015), pp. 978–986.

Moore, D., Raghupathy, A. and Maltz, W., Application of phase change materials in handheld computing devices, Thermal Measurement, Modeling & Management Symposium (SEMI-THERM) proceedings, (2016), pp. 213–217.

San, A. and Karaipakli, A., Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material, Applied Thermal Engineering 27 (2007), pp. 1271–1277.

Skach, M., Arora, M., Hsu, C.H., Li, Q, Tullsen, D., Tang, L. and Mars, J., Thermal Time Shifting: Decreasing Data Center Cooling Costs with Phase-Change Materials, IEEE Internet Computing, Vol. 21 (2017), pp. 34–43.

Shao, L., Raghavan, A., Emurian, L., Papaefthymiou, M. C., Wenisch, T. F., Martin, M. M. K. and Pipe, K. P., On-chip Phase Change Heat Sinks Designed for Computational Sprinting, Thermal Measurement, Modeling & Management Symposium (SEMI-THERM) proceedings, (2014), pp. 213-217.

Stupar, A., Drofenik, U., and Kolar, J. W., Optimization of Phase Change Material Heat Sinks for Low Duty Cycle High Peak Load Power Supplies, IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 2, No. 1 (2012), pp. 102-114.

Wang, T.-Y. and Chen, C. C. P., SPICE-Compatible Thermal Simulation with Lumped Circuit Modeling for Thermal Reliability Analysis based on Modeling Order Reduction, International Symposium on Signals, Circuits and Systems. Proceedings, (2004).