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Improvement of the Thermal Performance of PCM-Based Heat Sink Used in Electronic Cooling by Adding Nanoparticles

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Anahtar Kelimeler

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Graphical/Tabular Abstract (Grafik Özet)

In this study, nanoparticles such as TiO_2 and CuO were added to PCM and such a modified PCM is used in a finned heat sink. The thermal behavior of the PCM with addition of 1%, 2% and 5% TiO_2 and CuO was investigated numerically in three dimensions./ Bu çalışmada, PCM'ye TiO_2 ve CuO gibi nanopartiküller eklenmiş ve bu şekilde modifiye edilmiş bir PCM, kanatlı bir ısı emicide kullanılmıştır. %1, %2 ve %5 oranlarında TiO_2 ve CuO ilavesiyle PCM'nin ısıl davranışı üç boyutlu olarak sayısal olarak incelenmiştir.

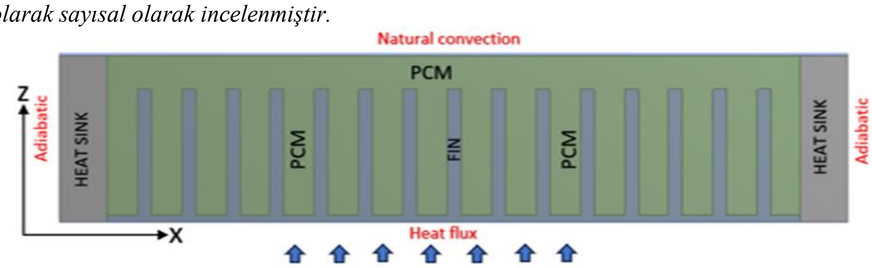

***Figure A*: . *Schematic diagram of physical domain (Symmetry of front view) /**Şekil A:**. Fiziksel alanın şematik resmi (Önden görünüşün simetrisi)*

Highlights (Önemli noktalar)

- *It was shown that as the nanoparticle ratio increases, thermal conductivity of the PCM rises and the melting time of nanoparticle PCM (Nano-PCM) is less than that of pure PCM./ Nanopartikül oranı arttıkça, PCM ısı transfer katsayısının yükseldiği ve nano tabanlı PCM erime süresinin saf PCM'den daha az olduğu görüldü.*
- *In this study, a maximum improvement of approximately 20.37% was achieved in heat sink base temperature by using Nano-PCM, which contains CuO./ Bu çalışmada, CuO ihtiva eden Nano tabanlı PCM kullanıldığında, ısı emici taban sıcaklığındaki maksimum iyileşme yaklaşık %20.37 olmuştur.*
- *The lowest heat sink base temperature was 129.01°C, observed with 5% CuO concentration./ En düşük ısı emici taban sıcaklığı, CuO'in %5 konsantrasyonunda PCM'ye eklenmesi ile 129.01°C olarak elde edilmiştir.*

Aim (Amaç): *In the study, it was aimed to increase the heat transfer rate by increasing the conductivity of PCM by adding nanoparticle to PCM./ Çalışmada, PCM'ye nanopartikül eklenerek PCM'nin iletkenliği artırmak ve dolayısıyla ısı transfer hızının artırılması hedeflenmiştir.*

Originality (Özgünlük): *In literature, a few studies have examined and compared the usage of a certain PCM with different nanoparticles, especially at different concentrations. Thus examining the thermal behavior of Nano-PCMs created by different nanoparticles at different concentrations is important and sheds light on researchers and commercial users./ Literatürde, sadece birkaç çalışma belirli bir PCM'nin farklı nanopartiküllerle, özellikle farklı konsantrasyonlarda kullanımını incelemiş ve karşılaştırmıştır. Bu nedenle farklı nanopartiküller tarafından farklı konsantrasyonlarda oluşturulan Nano-PCM'lerin termal davranışını incelemek önemlidir ve araştırmacılara ve ticari kullanıcılara ışık tutar.*

Results (Bulgular): *In heat sink using pure PCM, the average base temperature was 162 °C and compared to heat sink using Nano-PCM, a difference of approximately 33 °C in base temperature was observed./ Saf PCM kullanılan ısı emicid, ortalama taban sıcaklığı 162 °C olarak bulunurken, Nano tabamlı PCM kullanılan ısı emici ile karşılaştırıldığında, taban sıcaklığında yaklaşık 33 °C'lik bir fark gözlendi.*

Conclusion (Sonuç): *Highest thermal conductivities of Nano-PCM and the lowest heat sink base temperature were obtained by using CuO concentrates of 5%. Additionally, similar results were found for all concentrations of TiO_2 and CuO./ Nano tabanlı PCM'nin en yüksek termal iletkenliği ve en düşük ısı emici taban sıcaklığı, %5'lik CuO konsantreleri kullanılarak elde edildi. Ayrıca, TiO_2 ve CuO'in tüm konsantrasyonlarında birbirine yakın sonuçlar bulundu.*

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Abstract

Recently, thanks to the technological advances, electronic devices are getting smaller in size. This causes an increase in the heat generation per unit area. This heat has to be removed from electronic devices for them to be longer-lasting, more efficient and more reliable. There are many active and passive methods designed for this objective. One of them is embedding phase change material (PCM) in the heat sink. PCM, during the phase change stage, absorbs the heat generated in the system and thus aids in keeping the temperature at a certain value. The biggest downside of PCM is its rapid conduction of heat. PCM properties can be improved by using nanoparticles. In this study, nanoparticles such as TiO_2 and CuO were added to PCM and such a modified PCM is used in a finned heat sink. The thermal behavior of the PCM with addition of 1%, 2% and 5% TiO_2 and CuO was investigated numerically in three dimensions. RT-28HC was used as the PCM in the study. It was shown that as the nanoparticle ratio increases, thermal conductivity of the PCM rises and the melting time of nanoparticle based PCM (Nano-PCM) is less than that of pure PCM. However, it was observed that, the melting time of PCM with CuO added is longer than that of the PCM with TiO_2 added.

Elektronik Soğutmada Kullanılan PCM Tabanlı Isı Emici Termal Performansının Nanopartiküller Eklenerek İyileştirilmesi

Makale Bilgisi

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Öz

Son zamanlarda, teknolojik gelişmeler sayesinde elektronik cihazların boyutu oldukça küçülmektedir. Bu durum birim alan başına üretilen ısının artmasına neden olmaktadır. Elektronik cihazların daha uzun ömürlü, verimli ve güvenilir olması için bu ısının elektronik cihazlardan uzaklaştırılması gerekmektedir. Bu amaçla tasarlanmış birçok aktif ve pasif yöntem bulunmaktadır. Bunlardan biri de ısı emiciye faz değişim malzemesi (PCM) yerleştirmektir. PCM, faz değişimi aşamasında sistemde üretilen ısıyı emer ve böylece sıcaklığın belirli bir değerde tutulmasına yardımcı olur. PCM'nin en büyük dezavantajı, ısıyı hızlı iletmesidir. PCM özellikleri, nanopartiküller kullanılarak iyileştirilebilir. Bu çalışmada, PCM'ye TiO_2 ve CuO gibi nanopartiküller eklenmiş ve bu şekilde modifiye edilmiş bir PCM, kanatlı bir ısı emicide kullanılmıştır. %1, %2 ve %5 oranlarında TiO_2 ve CuO ilavesiyle PCM'nin ısıl davranışı üç boyutlu olarak sayısal olarak incelenmiştir. Çalışmada, PCM olarak RT-28HC kullanılmıştır. Nanopartikül oranı arttıkça, PCM termal iletkenlik katsayısının yükseldiği ve nano tabanlı PCM erime süresinin saf PCM'den daha az olduğu görüldü. Ancak, CuO eklenmiş PCM erime süresinin TiO_2 eklenmiş PCM'den daha uzun olduğu gözlemlendi.

1. INTRODUCTION (GİRİŞ)

In cooling of electronic devices, the most popular mechanism for expediting the heat transfer is using finned heat sinks. However, this method may not be sufficient for the latest generation compact electronic devices. High heat flux negatively affects the efficiency, lifespan and reliability of devices [1]. As a result, using different cooling methods in addition to finned heat sinks has become paramount. One way to improve heat conduction of a finned heat sink is integrating a Phase-Change Material (PCM) into it.

PCM-based heat sinks provide passive cooling in three stages. In the first step, the PCM draws heat

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from the electronic device and its temperature rises up to the melting point. In the following stage, the PCM starts melting at a constant temperature. In the last stage, the PCM completes melting and the temperature of the liquid begins to increase with the continuation of heat input. Although PCM absorbs a large amount of heat during melting, it may still take some time to complete melting [2]. Usage of a PCM-based heat sink is a preferred method in cooling systems due to the advantages of PCM, such as being non-toxic and non-corrosive, having high melting temperature and heat capacity, however the fact that these materials have a low thermal conductivity is a negative side.

To increase the thermal conductivity of PCM, materials as nanoparticles can be added to PCM in certain proportions [3-5]. There are both experimental and numerical studies in the literature on improvement of heat transfer of PCMs by adding nanoparticles to them. For example, in an experimental study, the effect of Cu nanoparticles on thermal conductivity of a PCM and phase change was studied [6]. By adding 2% Cu nanoparticles to paraffin, it was observed that there was an a 14.2% increase in the thermal conductivity, In another study [7], the thermal performance of Nano-PCM formed by adding AlO_2 was experimentally examined at different heat inputs and air temperatures. The results showed that adding a low amount of nanoparticles to pure PCM increased the heat sink performance by 2%. In another study, the thermal effects of using nano-healing PCM and pure PCM in a heat sink designed for cooling of an electronic chip were experimentally studied [8]. It was observed that Nano-PCM, created by adding 1% SiO_2 to PCM, provided an improvement by delaying the heating time by 220% compared to pure PCM. Different types of PCMs have also been used in numerous studies. In this study, the thermal behavior of Nano-PCMs, created by adding 0.2%, 0.5% and 0.8% graphene to RT-44HC and RT-64HC, were experimentally examined cooling electronic components [9]. At the end of the 90-minute period, it was observed that the best result was achieved by reducing %25 of the base temperature of the Nano-PCM obtained by adding 0.8% graphene to RT-44. In another study, a new Nano-PCM was obtained by mixing multilayered carbon nanotubes with paraffin to examine experimentally the effect of the electronic chip set on thermal performance [10]. It was observed that the newly developed Nano-PCM module reduces the melting time by 6% compared to paraffin.

Numerical studies on the thermal behavior of Nano-PCMs also exist in the literature. For example, the melting phenomenon of the mixture containing RT-28HC and Cu nanoparticles in a spherical container was investigated numerically in [11]. In the study, Nano-PCM formed by adding three different ratios of nanoparticles to PCM was examined and Stefan numbers were calculated. It was observed that, due to the reduction in the latent heat of Nano-PCM, both the thermal conductivity and the melting rate of the nanoparticles increased. In a different study, Nano-PCMs obtained by mixing various nanoparticles such as Al_2O_3, Fe_3O_4 and CuO with RT-35 and RT-50 were numerically examined in a two-stage mixing phenomenon in a triple tube [12]. The analysis result showed that using non-Newtonian PCM and Al_2O_3-based PCM decreased the melting rate by 37% and 47%, respectively. In a study about the melting phenomenon of paraffin wax, the melting rate was examined by adding Al_2O_3 into paraffin in different volume ratios [13]. As a result, it was observed that as the volume fraction in Nano-PCM of Al_2O_3 increased, the PCM melting rate also increased.

In the present study, CuO and TiO_2 were added within to RT-28HC at the concentrated of 1%, 2% and 5% to obtain different Nano-PCMs. Thermal performance of the Nano-PCMs based heat sink and melting phenomenon of Nano-PCM were investigated numerically at constant heat load. In addition, melting rate, thermal conductivity coefficient and latent heat values of Nano-PCMs were compared with each other. The most significant innovation of the current study improving the thermal conductivity of PCM-based heat sinks, which are used for cooling compact electronic devices, by adding nanoparticles into PCM at different concentrations. Relatedly, the main issue considered in this study is determining the optimum concentration of nanoparticle to be added into the PCM to ensure the best cooling performance. There are various studies where PCMs have been used within heat sinks for cooling electronic devices by passive methods. However, few studies have examined and compared the usage of a certain PCM with different nanoparticles, especially at different concentrations. Thus examining the thermal behavior of Nano-PCMs created by different nanoparticles at different concentrations is important and sheds light on researchers and commercial users. There is a high room for improvement of Nano-PCM heat sinks for electronic cooling. In the literature, to our best knowledge, there is no prominent study on comparison of Nano-PCMs created by adding CuO and TiO_2 with RT-28HC.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Description the problem (Problem tanımı)

In the numerical study, a Nano-PCM based finned heat sink was modeled in three dimensions. To reduce the computational burden, the symmetry of the design model was used in the analysis, as shown in Figure 1. Pin fins with dimensions of 2 x 2 x 20 mm3 were placed inside an aluminum block of 114 x 114 x 25 mm. In total, there are 225 pin fins in heat sink. The heat sink has a heater with 100 x 100 x 1 mm3. In the analyses, Al 6061 was chosen as the heat sink and fin material. Also, RT-28HC was used as PCM. CuO and TiO_2 were added into RT-28HC at the ratios of 1%, 2% and 5%, to increase the thermal conductivity of PCM. Thermophysical properties of RT-28HC, CuO and TiO_2 are given in Table 1. In the analyses, it was assumed that heat transfer occurred under passive convection conditions.

Table 1. Thermophysical properties of RT-28HC and nanoparticles (RT-28HC ve nanopartiküllerin termofiziksel özellikleri)

	RT-28HC [14]	CuO [15]	TiO_2 [16]
Thermal Conductivity(W/m.K)	0.2	18	8.95
Solid Temperature (K)	300	-	-
Liquid Temperature (K)	302	-	-
Specific heat (J/m.K)	2000	540	686.2
Dynamic viskosity (kg/ms)	0.00031	-	-
Density (kg/m^3)	880	6500	4250
Nanoparticle Diameter (m)	-	0.29 x 10^{-9}	0.21 x 10^{-9}

Nano-PCM based heat sink with different concentrations of CuO and TiO_2 were numerically analyzed in ANSYS Fluent software. Thermal conductivity of Nano-PCM is evaluated according to concentrations and types of the nanoparticles and varies depending on temperature. Therefore, the thermal conductivity of Nano-PCM was calculated in ANSYS by entering User Defined Function's (UDF's). The initial temperatures of the Nano-PCMs and aluminum heat sink, T_{ini}, was assumed to be 288 K.

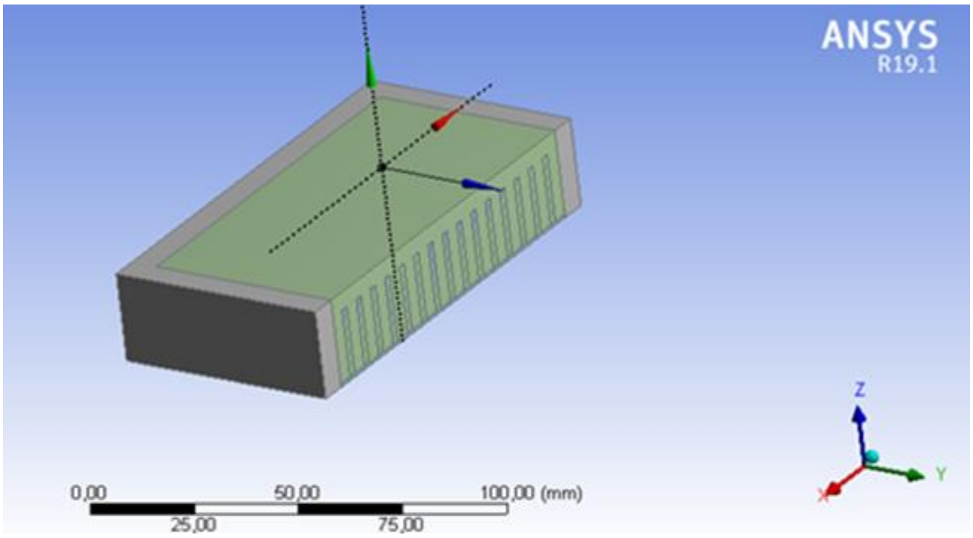


Figure 1. The three-dimensional isometric view of Nano-PCM heat sink (Nano tabanlı PCM ısı alıcının üç boyutlu izotmetrik görünümü)

Some assumptions were made during the analysis. These are listed below;

1. The fluid is Newtonian and incompressible.
2. According to the Boussinesq approach, the density of the molten PCM is constant except for the z-momentum equation. In z-momentum

equation, $q = qm/\beta(T - Tm) + 1$, where $Tm = (Ts + Tl)/2$ [17]

3. Volume change is neglected during PCM melting. Therefore, solid and liquid PCM densities are considered equal.

4. The lower part surface of the heat sink, except for the side wall and heat input surfaces, is insulated and it receives a constant heat flux of 4800 W/m^2 from the heater.

5. The upper surface of the heat sink is subjected to natural convection conditions.

6. Initially, both the fins and the PCM are at constant and the same temperatures.

Figure 2 shows physical domain that used in numerical analyses in current study.

In ANSYS Fluent, the mesh structures were created by using Patch Conforming Methods. While creating the mesh structure, care was taken to ensure that the maximum skewness value was less than 0.95 and the minimum orthogonal quality value was greater than 0.1. In figure 3, the mesh of Nano-PCM heat sink was presented.

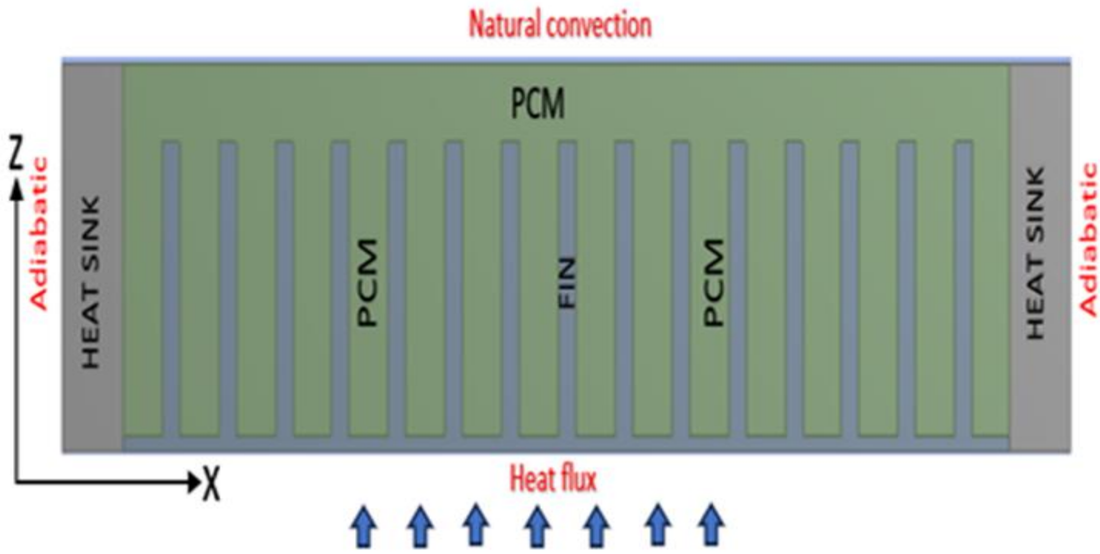


Figure 2. Schematic diagram of physical domain (Symmetry of front view) (Fiziksel alanın şematik resmi)

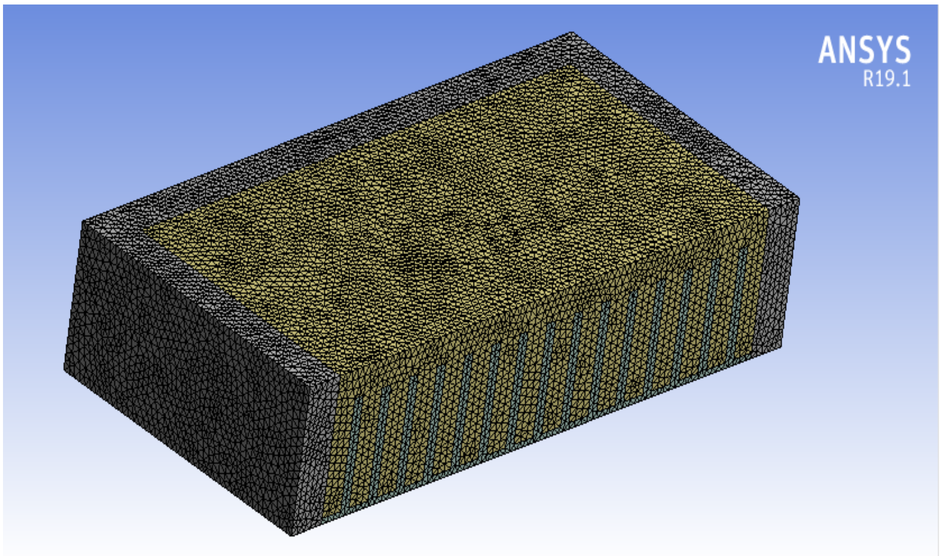


Figure 3. Mesh of the Nano-PCM heat sink (Nano tabanlı PCM'li ısı emicinin ağ yapısı)

2.2. Governing equations (Korunum denklemleri)

It was assumed that heat transfer occurs by convection in the aluminum parts of the design. The governing equations for convection are given below [18]:

$$\frac{\partial}{\partial t}(\rho_s.h)=\frac{\partial}{\partial x_i}\left(k_s\frac{\partial T}{\partial x_i}\right)+S \quad (1)$$

Here S stands for the source term. In the finned heat sink, PCM is filled into gaps between the fins and the model is designed in three dimensions. In the analysis, the flow was assumed to be laminar. The enthalpy-porosity technique was used to solve phase change problems with convective-diffusion controlled in the ANSYS program. Continuity equation [19]:

$$\frac{\partial\rho}{\partial t}+\rho.(\nabla.v)=0 \quad (2)$$

Momentum equation [19]:

$$\frac{\partial v}{\partial t}+\nabla.v=-\frac{1}{q}\nabla p+v\nabla^2 v+g+S \quad (3)$$

Energy equation [19]:

$$\frac{\partial(\rho H)}{\partial t}+\nabla.(\rho vH)=\nabla.(k\nabla T) \quad (4)$$

The term enthalpy used in Governing equations includes latent heat and specific heat value [15]. H given in equation (5) can be expressed as in equation (6).

$$H=h+H_L \quad (5)$$

The terms h and H_L given in equation (5) can be written as in equation (6) and equation (7), respectively. Sensible enthalpy is the sum of the determined enthalpy value and the temperature integral of the heat capacity.

$$h=h_{ref}+\int_{T_{ref}}^{T}C_p.dT \quad (6)$$

H_L represents the enthalpy difference and its value depends on the ratio of the liquid volume fraction, which varies between 0 and 1 [15].

$$H_L=f_l.L \quad (7)$$

In equation (6), L refers to the latent heat of the PCM and f_l refers to the liquid volume ratio of PCM. We can define the liquid volume ratio as in equation (8) [18]:

$$\begin{cases} f_l=0 \;\; if\; T<T_s \\ f_l=1 \;\; if\; T>T_l \\ f_l=\dfrac{T-T_s}{T_l-T} \;\; if\; T_s<T<T_l \end{cases} \quad (8)$$

In equation (9), the definition of the momentum source term S is given for the decrease of porosity in the melting zone [15].

$$S=\frac{(1-fl)^2}{fl^3+\varepsilon}A_{mush}\left(\vec{V}-\vec{V_p}\right) \quad (9)$$

Here ε is a very small nonzero number and usually set as 0.001. A_{mush} is a constant. $\vec{V_p}$ is the outward moving velocity of the solid area.

2.3. Nanomaterial thermophysical properties (Nanomalzeme termofiziksel özellikleri)

In this study, a Nano-PCM with new thermophysical properties was formed by adding different concentrations of CuO and TiO_2 to RT-28HC. A number of significant thermophysical properties of Nano-PCM were determined by the equations given in (10)-(13), respectively.

Density [20]:

$$q_{npcm}=\psi q_{np}+q_{pcm}(1-\psi) \quad (10)$$

Specific heat [20]:

$$C_{npcm}=\frac{\psi(q.C_p)_{np}+(1-\psi)(q.C_p)_{pcm}}{q_{npcm}} \quad (11)$$

Latent heat [20]:

$$L_{npcm}=\frac{(1-\psi)(q.L)_{pcm}}{q_{npcm}} \quad (12)$$

Dynamic viscosity [21]:

$$\mu_{npcm}=\mu_{pcm}(1+2.5\psi+6.2\,\psi^2) \quad (13)$$

In equations (10-13), ψ refers to the nanoparticle volume fraction.

The thermal conductivity of nano-PCM varies depending on many factors, such as temperature, melting rate and nanoparticle volume ratio. The correlation based on the Brownian Motion model for the thermal conductivity coefficient is given in the equation (14) [22].

$$k_{npcm} = \frac{k_{np} + 2k_{pcm} - 2(k_{pcm} - k_{np})\psi}{k_{np} + 2k_{pcm} + (k_{pcm} - k_{np})\psi} k_{pcm} + \frac{q_{np}\psi C_{np}}{2} \sqrt{\frac{\varkappa T}{3\Pi \mu_{pcm} d_{np}}} \quad (14)$$

Here dnp is the radius of nanoparticle. $\varkappa$ is the Boltzmann constant and is accepted as 1.381 x 10^{-23}.

2.4. Problem solving method (Problem çözüm metodu)

Governing equations were by using Finite Volume Methods. In this study, PISO algorithm was used to model the relationship between pressure and velocity and the First Order Up mind method was used to separate the momentum and the energy equations. The momentum and the continuity equations were iterated until the residuals converge to 10^{-6} and 10^{-3}, respectively.

2.5. Validation of numerical study (Nümerik çalışmanın doğrulanması)

The numerical analysis was confirmed with an experimental study performed by Zahid et al. [23]. In experimental study, the melting phenomenon of PCM based heat sink was explored at constant heat flux of 2.94 kW/m^2. RT-54 was selected and a heat sink with dimensions 116 x 116 x 32 mm^3 was used in the experimental study. In addition to this, a heater with dimensions of 101 x 101 x 1.2 mm was placed on the heat sink. The numerical analysis was performed based on the same boundary conditions and geometry as the experimental study. In figure 4, the temperature profile outcomes of heat sink in the numerical and experimental studies is given. The results of these two studies were compared with the root mean square (R^2) method and the R^2 value was calculated as 0.9678. This shows that the numerical study is capable of approximating the results of the experimental study.

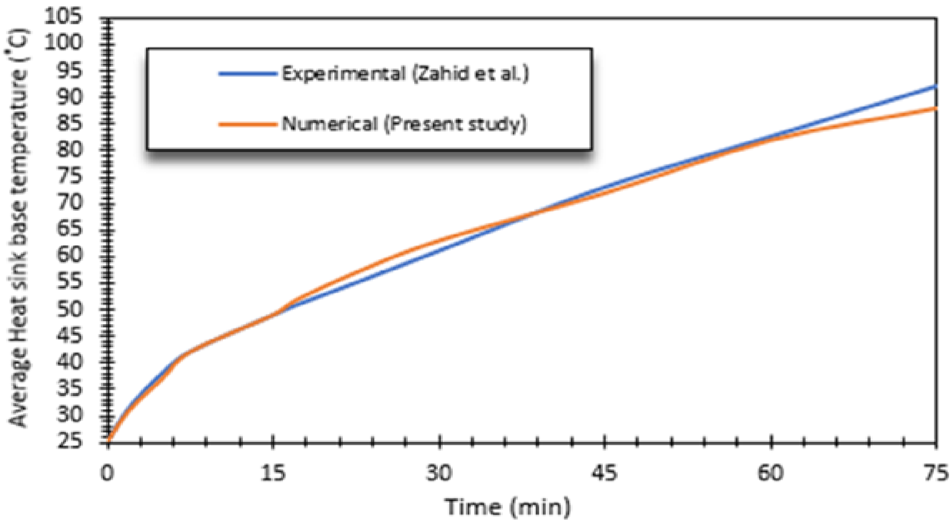


Figure 4. Validation of numerical study (Nümerik çalışmanın doğrulanması)

2.6. Mesh indepence (Mesh bağımsızlığı)

The designed model was divided into sub-regions as fin, PCM and heat sink. The mesh structures were created separately for each sub-region, for accurate analysis. To ensure independence of the results from the number of cells, three different mesh structures were created with element sizes of 1, 1.5 and 2 mm and the analyzes were performed under the same boundary conditions. Figure 5 shows the temperature profile of heat sink obtained for three different mesh element sizes. In the figure, it can be seen that similar temperature profiles are obtained in all models. Consequently, 1.5 mm was set as the element size. However, since it was thought that the time step in the analysis could also affect the results, analyses were carried out for time steps of 0.2, 0.5 and 1 s and the temperature values obtained are given in Figure 6. It can be seen that difference time steps did not cause a significant change in the average heat sink temperature profile. For this reason, the time step was set as 0.5 s.

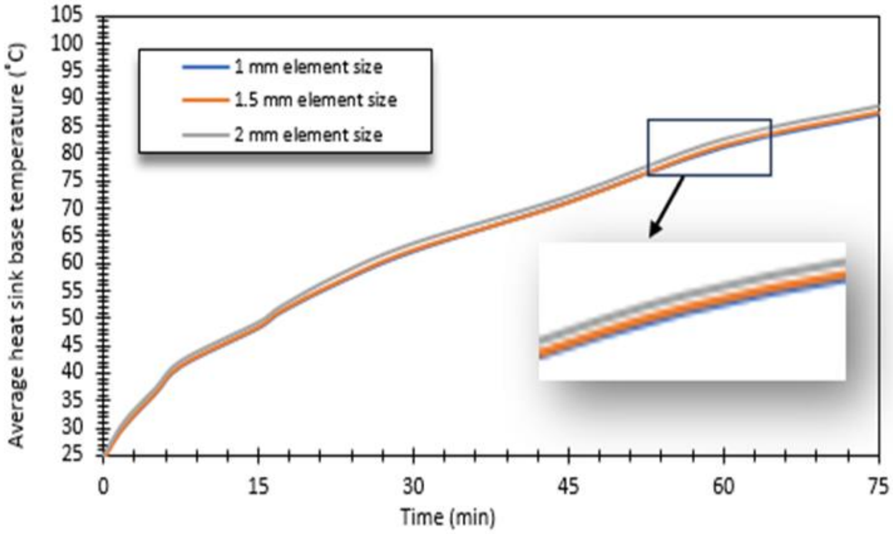


Figure 5. Mesh independence of numerical study (Nümerik çalışmanın mesh bağımsızlığı)

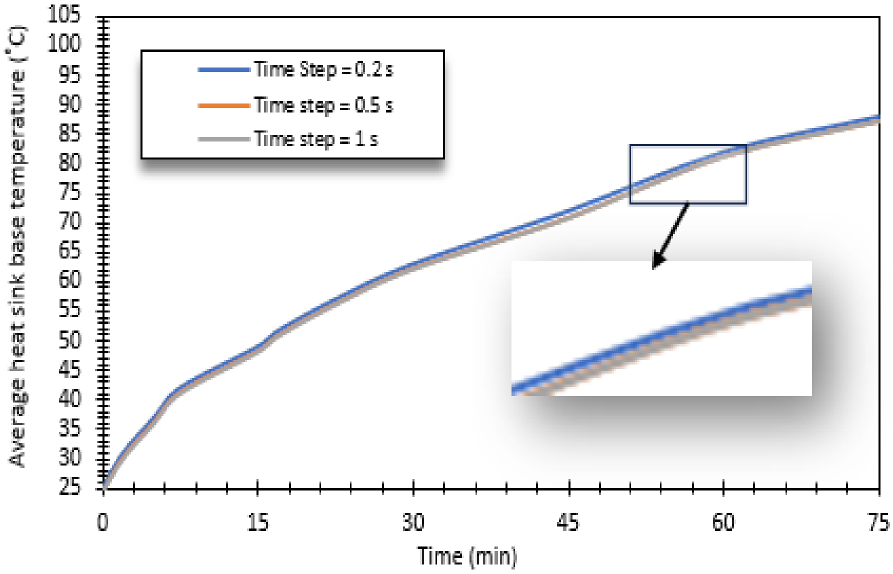
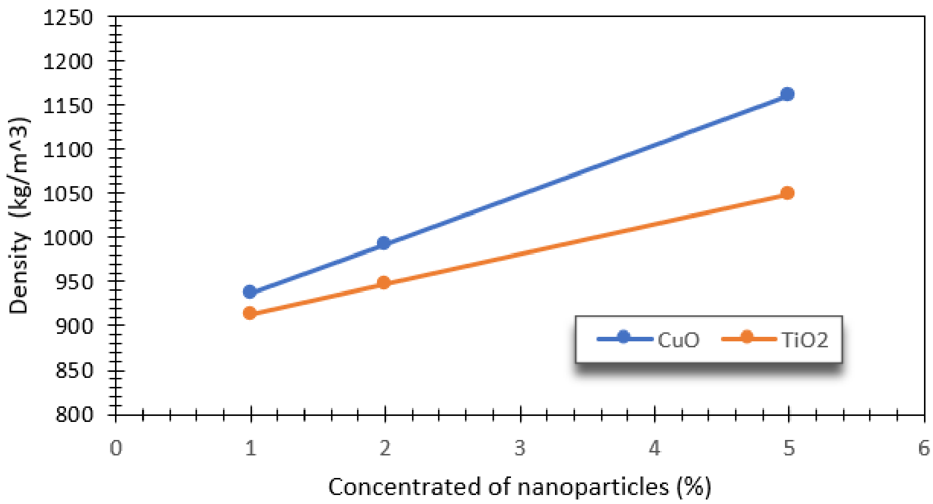


Figure 6. Temperature distribution of average heat sink base temperature for different time step size
(Ortalama ısı emici taban sıcaklığının farklı zaman adımlarına göre dağılımı)

3. RESULTS

By adding certain concentrations of nanoparticles to the PCM material, some thermophysical properties of the PCM can be varied. Figure 7 shows the variation of the properties such as density, specific heat capacity and latent heat of Nano-PCM with respect to the CuO and TiO_2 concentrations within the PCM. Accordingly, as the nanoparticle concentration raised, the density increased and the latent heat and specific heat decreased. In addition, it was concluded that, CuO addition caused a more significant change in the thermophysical properties of RT-28HC than TiO_2 addition did.

a.



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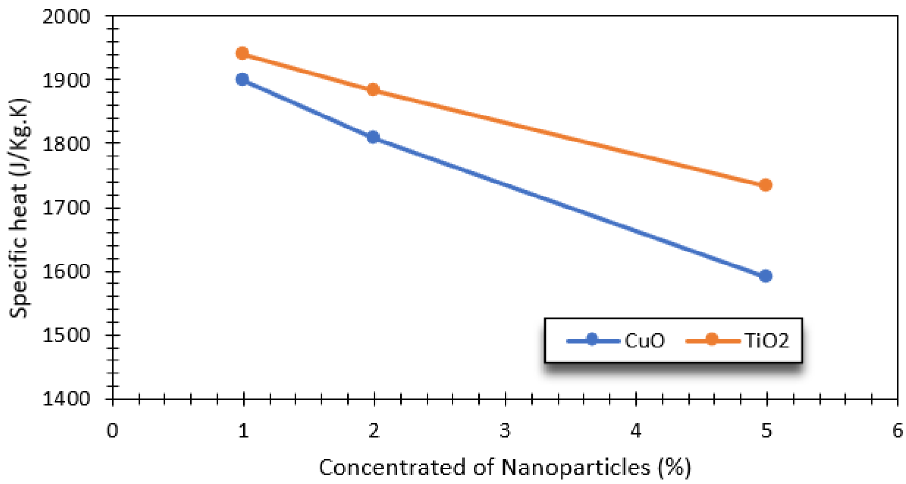

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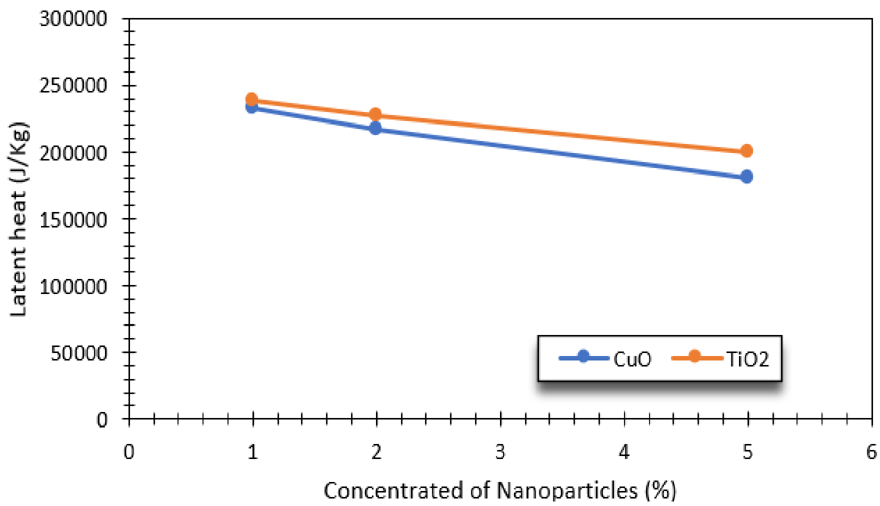

Figure 7. Properties of Nano-PCMs containing different concentrations of nanoparticles, **a.** density, **b.** specific heat, **c.** latent heat (Farklı nanopartikül konsantrasyonları içeren Nano-PCM'lerin özellikleri, **a.** yoğunluk, **b.** özgül ısı, **c.** gizli ısı)

In ANSYS Fluent, thermophysical properties of Nano-PCM, the initial and boundary conditions of designed model were initialized for simulations. In analyses, it was assumed that a constant heat flux of 4800 W/m^2 was transferred from the heater to the heat sink. After about 8400 iterations, temperature and melting rate contour graphs were plotted with the outcomes of the analyses. In Figure 8, the temperature contour graph of the Nano-PCM based heat sink were given at times of 1200, 3600, 5400 and 8400 s for a CuO concentration of 5%. In Figure 9, melting rate contour graphs were given at the time of 1200, 1800, 2400, 3600 s for the same Nano-PCM mentioned in figure 8.

In figure 10, variations of average heat sink base temperature with respect to time are given for different concentrates of nanoparticles. On the same chart, variation of average heat sink base temperature with respect to time for pure PCM is also shown. Accordingly, it was observed that the base temperature of PCM based heat sink increased up to 162 °C, while the base temperature of Nano-PCM heat sink reached only 131 °C.

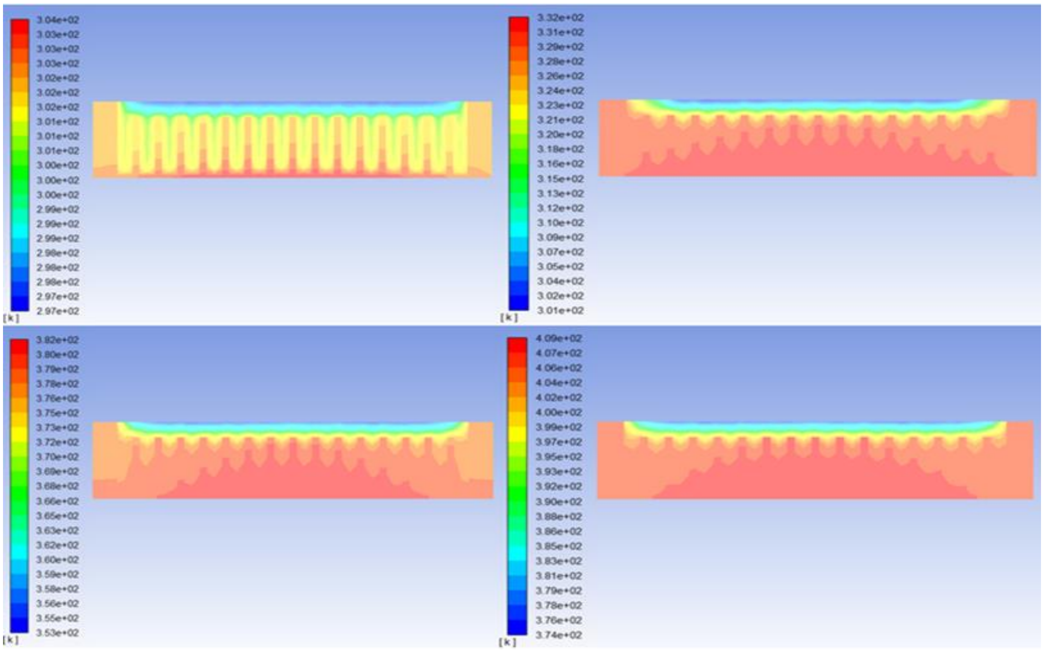

Figure 8. Temperature contour graphs of %5 CuO-Nano-PCM at the time of 1200, 3600, 5400, 8400 s
(% 5CuO konsantrasyonlu Nano tabanlı PCM'nin 1200, 3600, 5400 ve 8400 s'deki sıcaklık kontur grafiği)

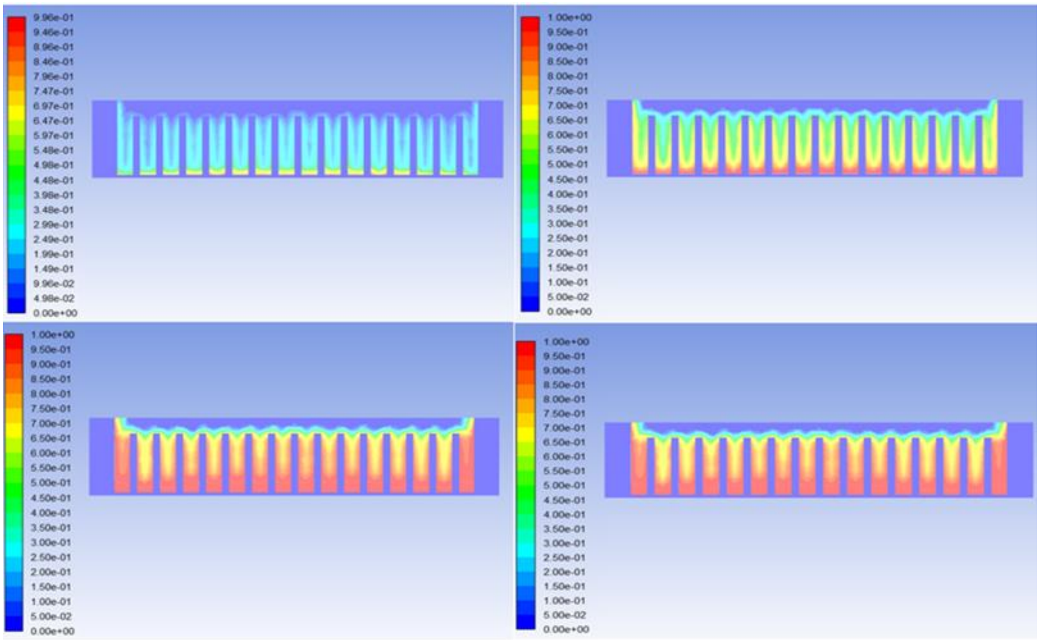

Figure 9. Melting rate contour graphs of %5 CuO-Nano-PCM at the time of 1200, 1800, 2400, 3600 s
(%5 CuO konsantrasyonlu Nano tabanlı PCM'nin 1200, 1800, 2400 ve 3600 s'deki erime kontur grafiği)

In figure 11, variations of the melting rate of Nano-PCM with respect to time were given for different concentrates of the nanoparticles. As can be seen from the chart, while very close melting times were obtained in the analyzes using Nano-PCM, the melting time was longer for pure PCM.

Similarly, in figure 12, variation of the thermal conductivity of different Nano-PCMs and pure PCM with respect to time were given. It can be seen that, the thermal conductivity of pure PCM does not change with temperature, while Nano-PCMs' thermal conductivities increase depending on the concentrates and type of nanoparticles.

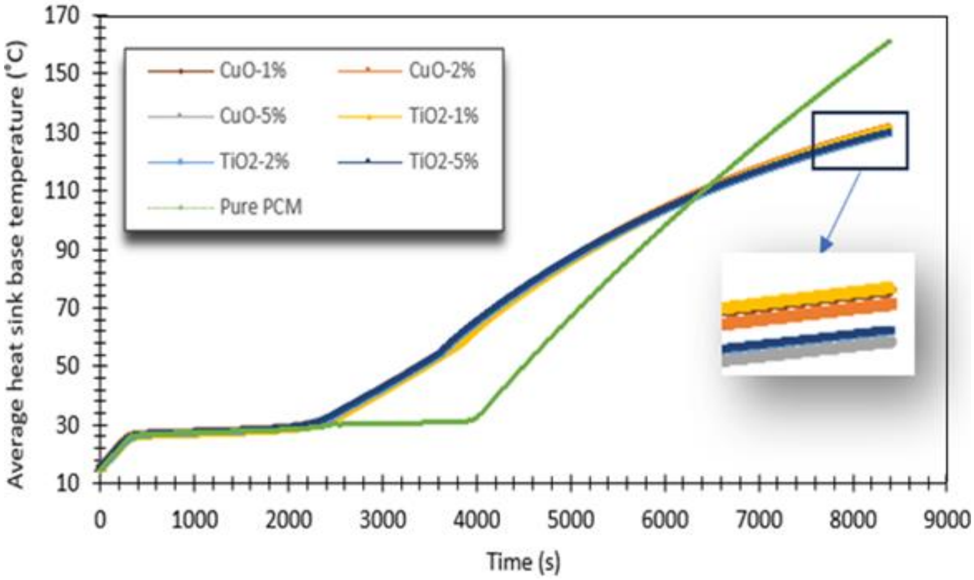

Figure 10. Temperatures of heat sink depending on time for using Nano-PCMs (Nano tabanlı PCM'lerin zamana bağlı ısı emici sıcaklık dağılımı)

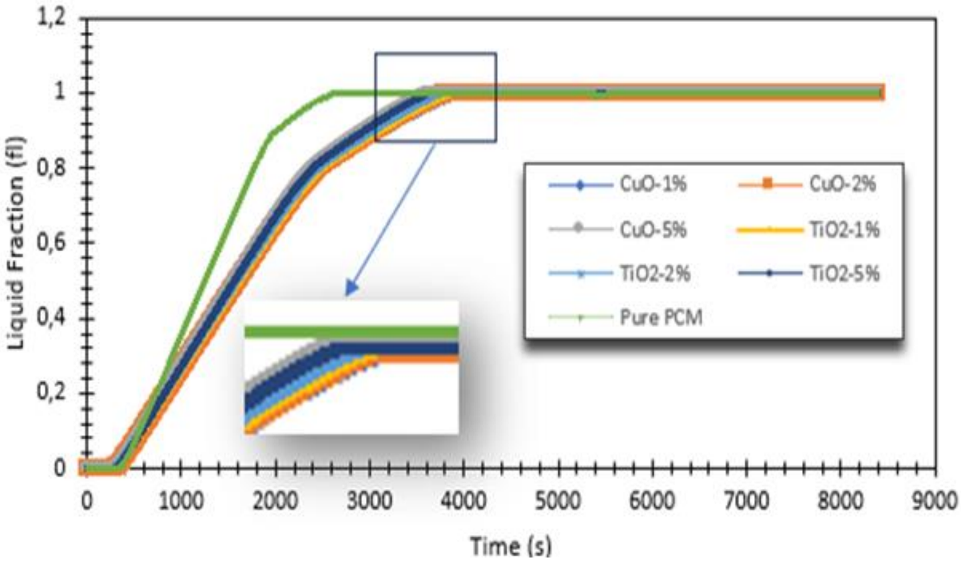

Figure 11. Melting rates of Nano-PCMs depending on time (Nano tabanlı PCM'lerin zamana bağlı erime oranları)

In table 2, the comparison of the results obtained in this study with some studies in the literature is given.

This comparison depicts the effects of PCM and nanoparticle type and the concentration of nanoparticle added to the PCM on thermal conductivity, heat sink base temperature and melting time

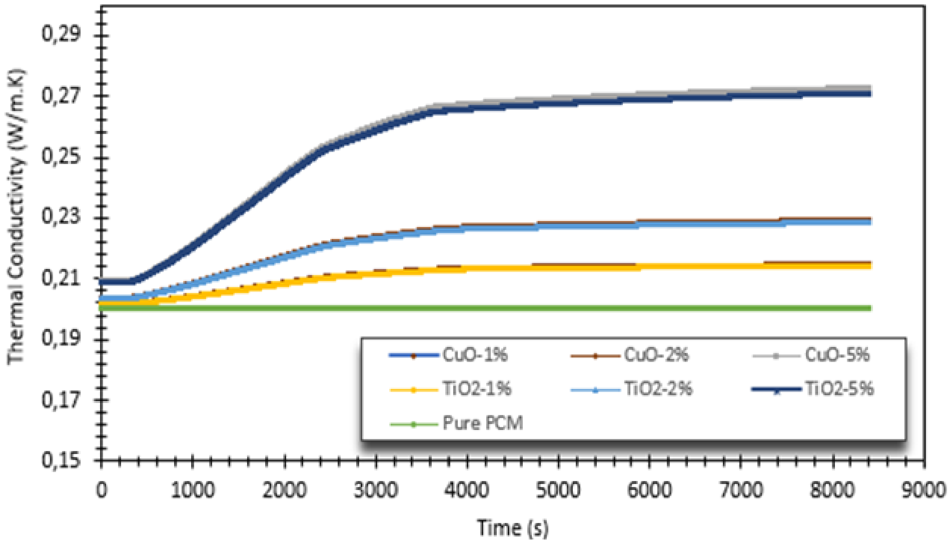

Figure 12. Thermal conductivities of Nano-PCMs depending on time (Nano tabanlı PCM'lerin zamana bağlı termal iletkenlikleri)

Table 2. Comparison of results from similar studies (Benzer çalışmaların karşılaştırılması)

Source	Methods/Heat flux input (W/m^2)	Heat Sink size (mm^3)	PCM/Nanoparticle (ψ)	Improving the thermal conductivity of PCM	Improvement in base temperature of heat sink	Melting time
Present Study	Numerical/4800	114 x 114 x 25	RT-28HC/CuO,TiO_2 (0.01,0.05)	35.5% (0.05, CuO) 7% (0.01,CuO)	20.37% (0.05, CuO) 19%11(0.01, CuO)	44.1% (0.01, CuO)
Wu et al.[6]	Experimental	-	Paraffin/Cu (0.01, 0.02)	18.1% (0.02)	-	33.3% (0.01,Cu)
Tariq et al. [9]	Experimental/2400	102 x102 x 25	RT-64HC/GNPs (0.005) Rt-44HC/GNPs (0.008)	-	16.37% 25.00%	-

4. CONCLUSION

In this study, it was aimed to achieve thermal performance improvement by adding nanoparticles into the PCM for PCM-based heat sink model used in electronic cooling. CuO and TiO_2 of concentrates of %1, %2 and %5 were added into RT-28HC as nanoparticles. The thermal behavior of Nano-PCM heat sink was investigated numerically with a heat flux of approximately 4800 W/m^2 supplied from the heater. The results obtained from the analyses were as follows;

- By adding nanoparticles to RT-28HC, some properties of Nano-PCM, such as density, specific heat capacity, latent heat and thermal conductivity, were altered. It was observed that, as the nanoparticle concentration in PCM increased, PCM density raised, but specific and latent heat were reduced. While the density, specific and latent heat of Nano-PCM did not change with respect to temperature, thermal conductivity increased with respect to temperature at constant concentrates of nanoparticle.
- The lowest heat sink base temperature was 129.01°C, observed with 5% CuO concentration and it was seen that the heat sink base temperatures were close to each other while using Nano-PCM. However, in heat sink using pure PCM, the average base temperature was 162 °C and compared to heat sink using Nano-PCM, a difference of approximately 33 °C in base temperature was observed.
- In [9], a maximum improvement of 16.37% in base temperature was achieved with Nano-PCM

formed by adding GNPs within RT-64HC at high concentrates. In addition, in same study, a improvement of 25 % in base temperature was achieved with RT-44HC/GNPs. In this study, an improvement of approximately 20.37% was achieved by using Nano-PCM, which contains CuO.

- Although the melting time of pure PCM and Nano-PCM were close to each other, it was observed that the melting time of pure PCM was longer.
- Highest thermal conductivities of Nano-PCM were obtained as 0.272 W/m.K by using CuO concentrates of 5% and as 0.271 W/m.K by using TiO_2 concentrates of 5%. As the thermal conductivity increased by 18.1% in [6], an increase of 35.5% was achieved in this study.

In the present study, nanoparticles as CuO and TiO_2 are added within RT-28HC in various concentrates and the Nano-PCMs were used in a heat sink for thermal management of electronic devices. Thus, it was aimed to increase the heat transfer rate by increasing the conductivity of PCM. In future studies, The Nano-PCMs be also implemented for micro channeled heat sinks used for thermal management of electronics.

DECLARATION OF ETHICAL STANDARDS
(ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Burcu ÇİÇEK*:** She conducted numerical analyses, commented the results and performed the writing process.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

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Abbreviations

AL	Aluminum
PCM	Phase change material
Nano-PCM	Nanoparticle enhanced phase change materials
UDF	User define function

List of symbols

Amus	Mushy Zone constant
Cp	Heat capacity (J/kg.K)
d	Diameter of PCM (m)
g	Gravitational acceleration, m/s^2
h	Sensible enthalpy (J/kg)
H	Enthalpy (J/kg)
H_L	Difference of enthalpy (J/kg)
k	Heat conductivity (W/m.K)
L	Latent heat (J/kg)
fl	Liquid fraction (1)
p	Pressure (Pa)
q”	Heat flux (W/m^2)
S	Source term
t	Flow time (s)
T	Temperature (˚C)
x, y, z	Cartesian coordinates (m)
v	Velocity vector (m /s)

Greek symbols

β	Thermal expansion coefficient (1/K)
ρ	Density (kg/m^3)
ψ	Nanoparticle volume fraction

Subscripts

f	Fin
in	Inlet
l	Liquid
m	Molten
np	Nanoparticle
PCM	Phase change material
ref	Referance
s	Solid