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Enhancing Smartphone Circuit Cooling: A Computational Study of PCM Integration

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ABSTRACT

Modern smartphones are used for a variety of demanding tasks, including gaming, high-resolution photography, and internet browsing, which greatly increases their power consumption. This elevated power usage generates more heat within the device, typically ranging from 2 to 6 watts. To manage this heat and maintain optimal performance, smartphones employ several cooling techniques. A new approach to mobile cooling could involve innovative methods such as advanced phase change materials, liquid cooling systems, or emerging technologies like thermoelectric and microfluidic cooling. This paper introduces a new cooling method utilizing phase change materials, which absorb heat by transitioning between solid and liquid states. This technique helps maintain the device's temperature below 75°C. In mid-range smartphones, cooling techniques such as natural convection, indirect heat-pipe cooling, and forced convection are commonly employed, but these methods often prove inadequate under high-power usage conditions.

1.Introduction

In the rapidly evolving world of smartphones, maintaining optimal performance under increasingly demanding applications has become a critical challenge. Modern smartphones are multifunctional devices, performing tasks such as high-definition gaming, intensive camera operations, and continuous internet connectivity, all of which significantly increase their thermal loads. This surge in heat generation not only affects the performance and longevity of electronic components but also poses risks to user safety and device reliability. Traditional cooling methods, such as natural convection, heat pipes, and forced air systems, often fall short in addressing the heat dissipation needs of modern smartphones, especially during prolonged high-power usage. These methods, while effective to an extent, are often constrained by the compact and dense nature of smartphone designs, leaving little room for effective heat management solutions. As a result, there

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is an increasing demand for innovative cooling strategies that can efficiently manage the thermal output of high-performance smartphones without compromising on size, weight, or battery life. One promising approach to this problem is the integration of Phase Change Materials (PCMs) into smartphone circuit designs. PCMs have the unique ability to absorb and store large amounts of latent heat during phase transitions, typically from solid to liquid, which can be harnessed to stabilize the temperature of electronic components.

Unlike traditional cooling systems, PCM-based solutions offer passive thermal management, requiring no moving parts or additional energy input, making them ideal for compact devices like smartphones. This paper presents a computational study on the integration of PCMs into smartphone circuit cooling systems. By simulating the thermal behavior of electronic components under various operational conditions, this study aims to explore the effectiveness of PCM-based cooling in maintaining device temperatures within safe operating limits. Kurhade *et al.,* [1] explained numerical investigation of the substrate board characteristics using different materials and noted that with the use of copper cladding board the velocity of air required for cooling the ECs is substantially reduced by 2m/s and the temperature of the IC chip is reduced by 1.50–11.12°C. Kurhade *et al.,* [2,3] explained Computational Study of PCM Cooling for Electronic Circuit of Smart-Phone and Thermal Control of IC Chips Using Phase Change Material: A CFD Investigation. Kurhade *et al.,* [4,5,6] explained the CFD Approach for Thermal Management to Enhance the Reliability of IC Chips and ANN-GA Approach for Efficient Thermal Cooling. The research focuses on key parameters such as the choice of PCM material, the placement of PCM layers, and the impact of continuous and intermittent usage patterns on thermal performance.

As smartphones become lighter and thinner, the heat dissipation rate from these power electronic components increases significantly [7]. Currently, smartphones rely on cooling methods such as natural air circulation, heat pipes, and fans. However, these traditional cooling techniques are often ineffective in handling the high heat generated by demanding smartphone applications [8]. Passive cooling systems, including those using phase change materials, are more cost-effective and energy-efficient compared to active cooling methods [9]. PCM-based cooling has become increasingly popular due to its ability to absorb heat and change state without requiring external energy, making it both cost-effective and energy-efficient. In contrast, a study by Ronan Grimes et al. proposed a fan-based cooling system for smartphones that cools the device by circulating air. However, this method is less energy-efficient as the fan requires power from the phone's battery [10].

A study focused on developing passive cooling solutions for laptops conducted computational fluid dynamics (CFD) simulations to optimize both active and passive cooling components within the laptop's complex internal structure. This research aimed to address the issue of overheating, which is often caused by the formation of hot spots due to the intricate layout of electronic components. [11] In recent times, numerous studies have experimentally validated the effectiveness of PCM-based solutions for cooling electronic systems. For instance, one study conducted a numerical analysis of a heat storage unit filled with PCM [12]. A numerical model was used to study how a PCM-filled open fin structure melts. Additionally, Setoh *et al.,* [13] conducted an experiment using a neicosane-based phase change material to improve the cooling performance of mobile phones.

A research study combined experimental and computer modeling techniques to investigate the use of phase change materials for cooling mobile devices. The study employed microencapsulated PCM and analyzed the impact of time on the maximum temperature of the electronic components [14]. Rahman and Raghavan [15] used natural and forced convection on four heat sources. Yadav and Kant [16] conducted experiments on vertical PCB-mounted heat sources, proposing a Nusselt number correlation. Alves and Altemani [17] analyzed laminar forced convection and proposed a predictive superposition principle. Yusoff *et al.,* [18] used Fluent for numerical simulations on a PLCC mounted on a PCB, noting improved thermal performance at higher air velocities. Narasimham [19] examined heat transfer from IC chips, emphasizing limitations and proposing alternatives like liquid immersion and heat sinks for enhanced dissipation. Pirasaci and Sivrioglu [20] empirically noted the improved dissipation at lower Reynolds numbers. He *et al.,* [21] explored flush-mounted heat source heat transfer on a horizontal channel with air, favoring high emissivity. Yu *et al.,* [22] introduced a new adaptive thermal management method for electronic devices. The system uses bionic sweating to provide extra cooling as temperatures rise, achieving 80% of the cooling capacity of fixed systems.

Key factors affecting the performance of this sweating cooling method are also explored. Liu *et al.,* [23] picks the best heat storing materials (PCMs) for various applications (0-100°C), explores improving heat storage and transfer, and reviews PCMs in electronics and battery cooling. Ajmera and Mathur [24] examined three heat sources mounted flush, considering both natural and mixed convection, suggesting strategic placement for optimal cooling. Chaurasia *et al.,* [25] numerically simulated six heat sources under mixed convection, observing a substantial temperature decrease. Bejan *et al.,* [26] explored design and thermal optimization across diverse systems using thermodynamics and heat transfer principles. Waware *et al.,* [27] provide critical reviews on heat transfer and Heat Transfer Enhancement in Tubular Heat Exchangers with Jet Impingement. Patil, P *et al.,* [28] used a water-based Al2O3 nanofluid was used in this work to grind materials due to its outstanding convective heat transfer and thermal conductivity qualities.

Additionally, Upadhe *et al.,* [29] explains water Saving and Hygienic Faucet for Public Places in Developing Countries. Kurhade *et al.,* [30-33] focuses on enhancing the thermal management of electronic components, specifically in Switch-Mode Power Supply (SMPS) boards. The research investigates how the thermal conductivity of the substrate board impacts component temperatures and evaluates the effectiveness of using Phase Change Materials (PCMs) for heat dissipation. Both numerical simulations and experimental tests were conducted to assess the effects of various substrate materials and cooling methods on the overall thermal performance of the components. Kurhade *et al.,* [34-37] also explores several sustainable energy applications. First, the study examines the performance of solar collectors made from recycled aluminum cans for drying applications. Secondly, an in-depth analysis evaluates the use of biodiesel blends from Calophyllum inophyllum and dimethyl carbonate in diesel engines, focusing on optimizing performance and reducing emissions. Lastly, the research investigates aerodynamic efficiency, analyzing aerofoil designs through computational fluid dynamics (CFD) simulations and wind tunnel testing. Furthermore, fuzzy logic techniques are applied to predict heat transfer improvements in heat exchangers using twisted tape inserts.

This research numerically analyzes a scaled-down model of a smartphone motherboard, including simulated IC chips and a battery. Paraffin wax, a cost-effective and non-reactive phase change material, was chosen for this study to target mid-range smartphones. Through this study, we aim to provide insights into the potential of PCM technology as a viable solution for the thermal management challenges faced by next-generation smartphones. By leveraging the latent heat absorption properties of PCMs, we propose a cooling strategy that not only enhances the reliability and performance of smartphone electronics but also aligns with the industry's push towards more energy-efficient and sustainable designs. The aim of this paper is to propose and evaluate an innovative cooling method for modern smartphones, utilizing phase change materials (PCMs) to manage heat generated by high-power consumption tasks. By exploring the effectiveness of PCMs, which absorb heat through solid-to-liquid transitions, this study seeks to maintain device temperatures below 45°C and improve overall thermal management, particularly in scenarios where traditional cooling methods such as natural convection, heat-pipe cooling, and forced convection are insufficient under high-performance demands.

2. Methodology

This study employs computational fluid dynamics (CFD) simulations using ANSYS Fluent software to examine the effectiveness of phase change material (PCM) in cooling smartphone components. A simplified smartphone model, including a battery, ICs, and a camera, was created and embedded in paraffin wax, a type of PCM. The properties are shown in table 1. The simulation compared the temperature behaviour of the device with and without PCM under specific conditions. The goal was to demonstrate the PCM's ability to improve the smartphone's cooling performance by preventing excessive temperature rise.

Table 1
Thermophysical properties of paraffin wax

Sl. No.	Property	Value
1	Density, kg/m3	748
2	Thermal conductivity, W/mK	0.26
3	Dynamic viscosity, Ns/m2	1.856
4	Specific heat, J/kgK	2944
5	Latent heat of fusion, kJ/kg	264
6	Melting point, ◦C	48.28 - 54.21

The study involved creating a digital representation of a smartphone's motherboard, including key components like the battery, processors (ICs), and camera. This model was then immersed in paraffin wax, a substance that changes phase from solid to liquid when it absorbs heat. Simulations were run to compare the temperature changes over time with and without the wax present. The wax's properties, including its melting point, were considered in the analysis. To understand the impact of PCM on smartphone cooling, a digital model was constructed representing the essential components of a smartphone's motherboard. This model included the battery, which is a significant heat source, as well as the ICs and camera, which can also generate heat. The model was then immersed in paraffin wax, a material known for its ability to absorb heat and undergo a phase change from solid to liquid. By simulating the device's operation under different conditions, researchers were able to compare the temperature distribution and changes over time with and without the presence of PCM. The melting point and other properties of paraffin wax were carefully considered in the simulations to accurately represent its cooling behaviour. The methodology has explained in Figure 1.

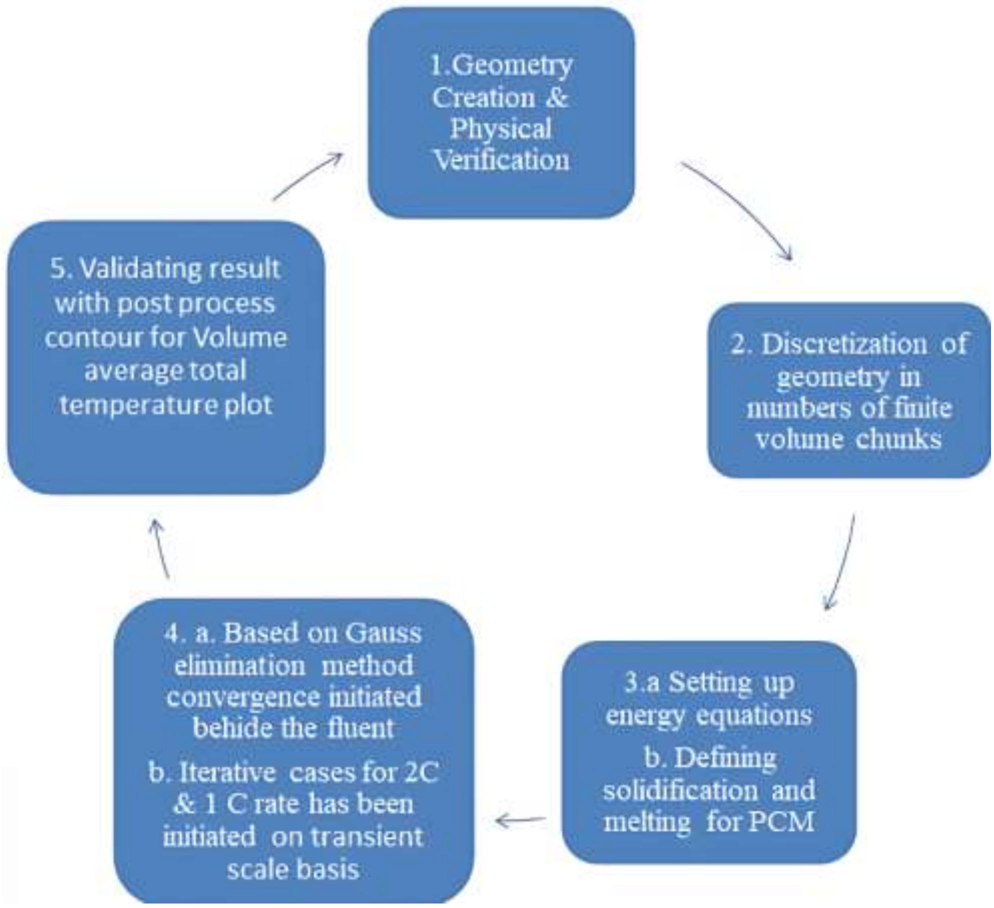

Fig. 1. Methodology adopted

2.1 Governing Equations

To accurately model the behaviour of the phase change material (PCM), the enthalpy porosity method was employed. This approach, introduced by Voller and Prakash [11], effectively captures the phase transitions and heat transfer within the PCM. The ANSYS Fluent solver was utilized, incorporating its specialized solidification and melting model. The mushy zone, where the PCM exists in a mixed solid-liquid state, was defined with a melting point of 105^0C.

The liquid fraction (α) of the PCM is a crucial parameter that indicates the proportion of the material in its liquid state. This value ranges between 0 and 1, with 0 representing a completely solid state and 1 representing a fully liquid state. As illustrated in Figures 2 and 3, α varies between these two extremes within the mushy zone. This representation allows for a precise simulation of the PCM's behavior during the phase change process. The selection of sizes of smartphone components like cameras, batteries from the data sheet provided by the manufacturer.

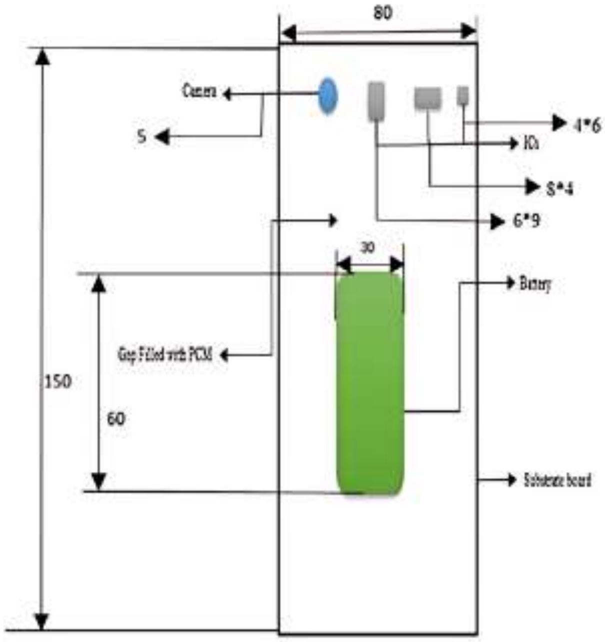

Fig. 2. Size and geometrical position

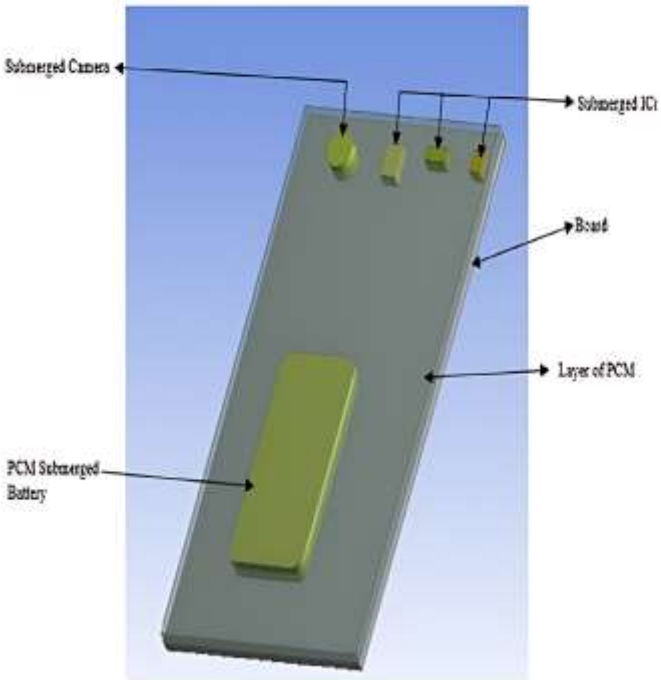

Fig. 3. Isometric view

2.1.1 Continuity equation

The generic 3-D continuity equation for the present simulation is given

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial w}=0 \tag{1}$$

2.1.2 Momentum equation

The enthalpy-porosity method models the partially solidified region, or mushy zone, as a porous material. The porosity of each cell is determined by the proportion of liquid within that cell. The reduction in porosity in the mushy zone results in a decrease in momentum, which can be represented by

$$S = -A(\beta)V \quad (2)$$

In the momentum equation, the source term represents the flow resistance within the porous medium. This term is influenced by the porosity function A(b). To ensure free movement in the liquid phase, the source term must be zero. However, in the solid phase, it needs to be substantial to restrict the velocity to near-zero values. Various functions can fulfill this requirement, but the Carman-Kozeny equation, derived from Darcy's law for fluid flow in porous media, is commonly used in a modified form.

$$A(\beta) = \frac{A_{mush}}{\alpha^4 + €} \quad (3)$$

In the equation, α represents the liquid volume fraction. To avoid dividing by zero, a very small value (e = 0.001) is assigned to the variable e. Amush is a constant that determines how quickly the fluid velocity decreases to zero during solidification. The momentum equation is provided in Eq. (4).

$$\frac{\partial(\rho V)}{\partial t} + \nabla(\rho V) = \nabla p + \mu \nabla^2 V + g\beta\,(T - T_\infty) \quad (4)$$

In the equation, ρ represents the density, k is the thermal conductivity, μ is the dynamic viscosity, V is the fluid velocity, p is the pressure, and g is the gravitational acceleration.

2.1.3 Energy equation

The total enthalpy (H) of the material is calculated by adding the sensible heat (Sh) and the latent heat (Lh), as shown in Eq. (5).

$$H = S_h + L_h \quad (5)$$

The latent heat content is expressed as the product of the liquid volume fraction (α) and the latent heat of the material (L). The energy equation for solidification and melting problems is presented in Eq. (6).

$$\frac{\partial(\rho H)}{\partial t} + \nabla(\rho v H) = \nabla(k \nabla T) \quad (6)$$

3. Boundary Conditions

The adiabatic condition is created at wall domain by assigning ambient temperature of 25 during initialization. The assignment of heat source is given in terms of Watt in input to the volume. The following are the boundary assumptions taken account during analysis.

i) Pressure based setup is used with bounded second order gradient momentum-based method.
ii) To assign heat source modeling for components energy equation is activated
iii) Solidification and melting model are activated to assign latent heat, solidification and melting thermo-physical property at PCM.
iv) Radiation is neglected
v) Conduction is main heat transfer mode of analysis
vi) 5 HTC is assigned at the solid walls to mimic natural convection behavior.

4. Grid convergence study

To ensure accurate results without excessive computational resources, the study also involved determining the optimal mesh size. This process, known as grid convergence independence study, helped fine-tune the simulation parameters for efficiency and precision. The phase change modeling in this study simulates the transformation of the PCM from a solid to a liquid state during melting and back to a solid during cooling. To accurately capture the complex interactions between the PCM and the electronic components, an additional layer of mesh elements (inflation layer) was added near their interface as shown in Figure 4. The simulation software was set to achieve a high level of precision with convergence criteria of 1e-6. The impact of different mesh sizes on the results is summarized in Table 2.

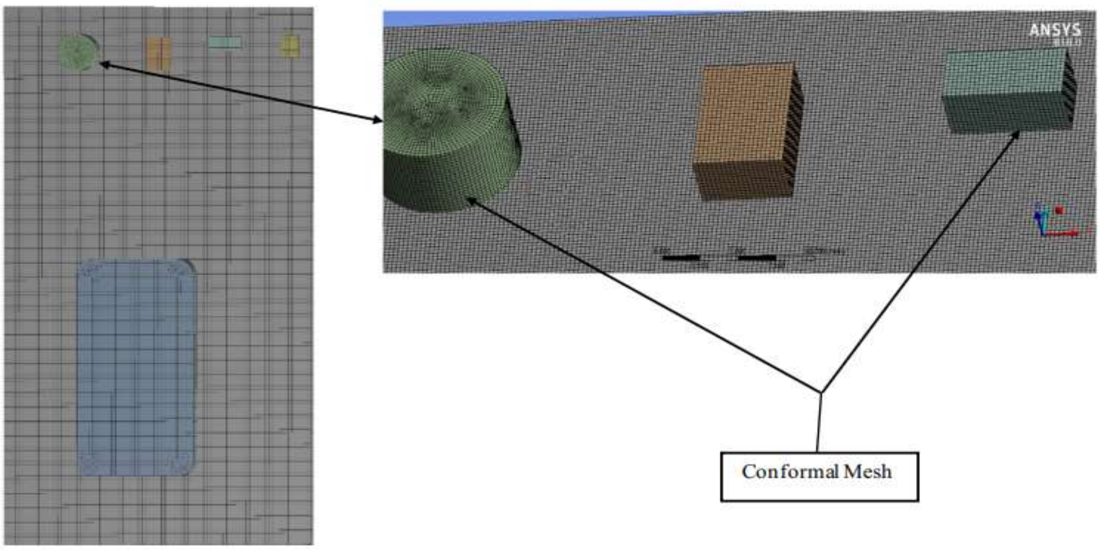

Fig. 4. Optimal mesh creation

Table 2
Grid independent study

Sl. No.	Nodes	Elements	Temperature ^{0}C	Time S
1	3850	2192	110	145
2	13256	7842	78	145
3	63458 (Selected)	47652	45.5	145
4	1869544	1659460	45	145

4. Validation

The accuracy of this CFD study was validated by comparing its results to a previous study by Tomizawa et al. [9] this earlier research demonstrated that using a thin PCM sheet can effectively delay the onset of high temperatures within electronic circuits. The PCM's ability to change from a solid to a liquid state within its volume plays a crucial role in dissipating heat from the electronic components.

5. Result

The comparative analysis is structured into two sections, each comprising two cases, totalling four cases overall. In Part 1, the study is conducted without phase change material (PCM), while in Part 2, the investigation is carried out with 95% of the system filled with PCM. The cases are defined by heat generation thresholds of 2°C and 1°C rates, with a fixed time scale until the battery reaches 55°C. The same conditions are then analyzed with PCM to observe any cooling effects.

Under the assigned boundary conditions, four cases are examined, divided into two main parts: Part 1 without PCM and Part 2 with PCM. The cases are as follows:

5.1 Part 1: With No PCM:

i) **Case a:** A threshold limit of 2°C up to 56°C is reached in 145 seconds. (Figure 5)
ii) **Case b:** A threshold limit of 1°C up to 56°C is reached in 430 seconds. (Figure 6)

In Part 1, without PCM, the analysis considers different temperature thresholds, reaching 56°C in 145 seconds for Case a and in 430 seconds for Case b. To compare and evaluate the cooling effect, the study then incorporates PCM around the electronic element, maintaining the same time scales of 145 seconds for the 2°C rate and 430 seconds for the 1°C rate, to determine the cooling impact achieved by the PCM as shown in Table 3.

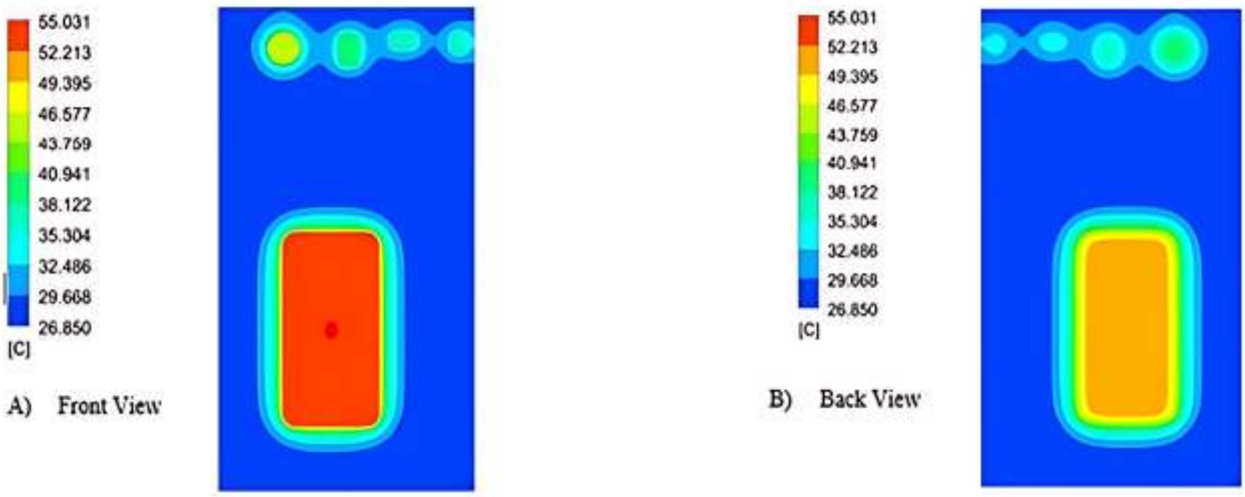

Fig. 5. Without PCM temperature contour

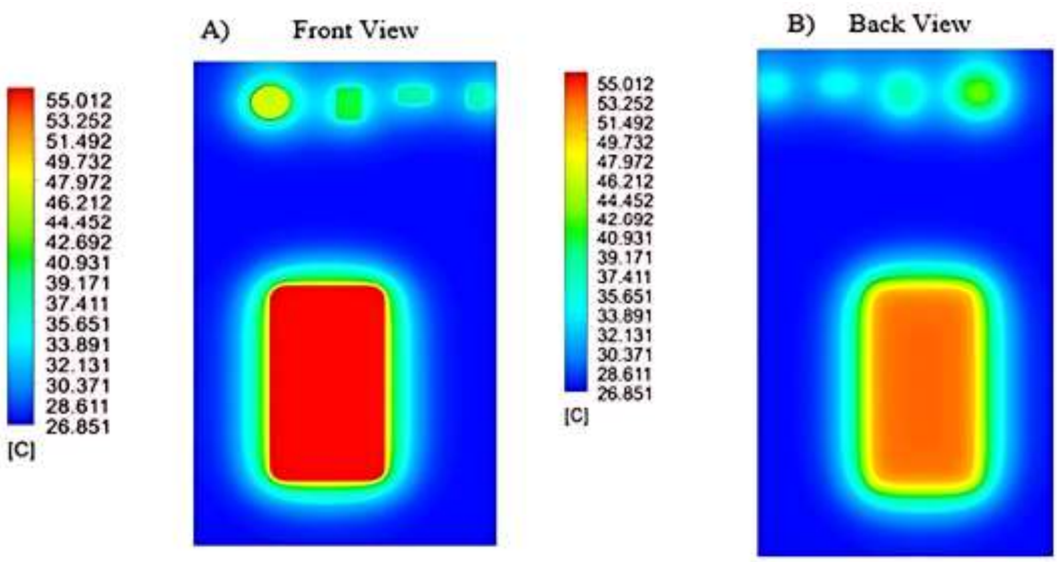

Fig. 6. Without PCM temperature contour at 1 C

Table 3
Without PCM

Rate of discharge	Rate of heat generation Battery w/m^3	Rate of heat generation at IC and Camera w/m^3	Temp. at IC ^{0}C	Temp. at Battery ^{0}C	Temp. at Camera ^{0}C
2C	608350	475902	42.018	53.65	43.2648
1C	406350	377902	41.248	54.13	42.719

5.2 Part 2: With PCM

i) **Case a:** 2°C rate with a pre-set time duration of 145 seconds (Figure 7)
ii) **Case b:** 1°C rate with PCM (Figure 8)

The smartphone model with phase-change material (PCM) significantly outperformed the model without PCM in temperature management. During a simulation with a 2°C heating rate, the PCM-equipped model reached the critical 49°C after 145 seconds. In contrast, the model without PCM reached 55°C, exceeding the critical threshold, within the same timeframe. This significant temperature reduction is illustrated in Figures 7 and 8. This temperature reduction is essential for ensuring the optimal performance of the electronic components, as outlined in Table 4.

Table 4
With PCM

Rate of discharge	Rate of heat generation Battery w/m^3	Rate of heat generation at IC and Camera w/m^3	Temp. at IC ^{0}C	Temp. at Battery ^{0}C	Temp. at Camera ^{0}C	Liquid Fraction
2C	608350	475902	30.028	46.85	34.658	0.01602153
1C	406350	377902	29.87	47.24	34.768	0.01465845

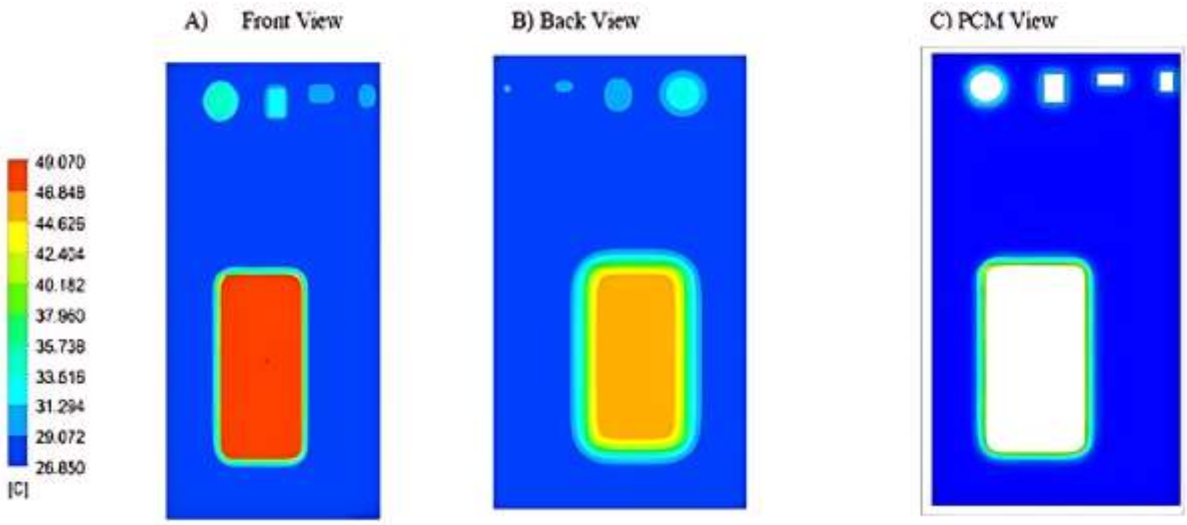

Fig. 7. With PCM at 2 C

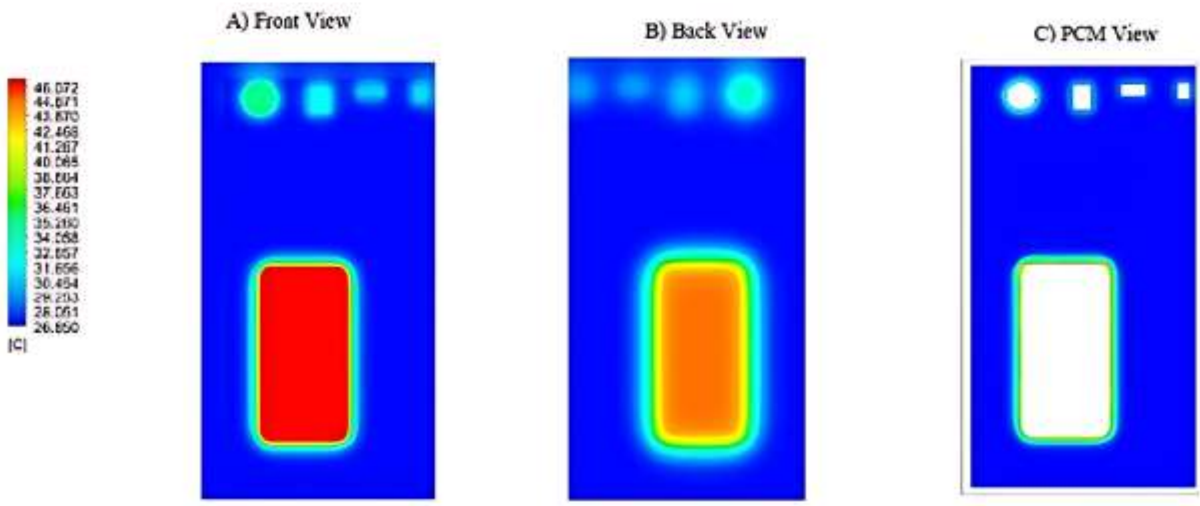

Fig. 8. With PCM at 1 C

The study conclusively demonstrated that PCM offers substantial benefits in enhancing the thermal management of smartphones. By effectively delaying the heating of components and improving heat transfer efficiency, PCM can help maintain lower operating temperatures, even under high-stress conditions. This not only prevents overheating but also allows smartphones to sustain peak performance for longer periods without the risk of thermal damage.

Moreover, the ability of PCM to keep the temperature below critical thresholds like 55°C is particularly beneficial in extending the lifespan of sensitive components such as the battery and processors. The research highlights the potential of integrating PCM into smartphone designs as a practical and efficient solution to the ongoing challenges of thermal management in increasingly powerful and compact devices. This advancement could lead to the development of smartphones that are not only more reliable but also capable of supporting more demanding applications without the drawbacks associated with overheating.

6. Conclusion

This research utilized computer simulations to explore the potential of phase-change material (PCM) as a cooling solution for smartphone components such as the battery, processors, and camera. The key findings are as follows:

i) Delayed Component Heating: The simulations revealed that PCM effectively absorbs heat generated by electronic components. As the temperature rises, the PCM undergoes a phase change from solid to liquid, absorbing substantial thermal energy. This process delays the temperature increase in the components, enabling the smartphone to maintain optimal operating conditions for a longer period, even under high-performance use.

ii) Efficient Heat Transfer: The study showed that the phase change not only absorbs heat but also facilitates efficient heat transfer away from critical components. The latent heat absorbed during the solid-to-liquid transition is effectively dissipated, resulting in faster cooling. This improved heat dissipation helps prevent thermal throttling, where the smartphone's performance is reduced to avoid overheating.

iii) Optimal Cooling Benefits: A comparative analysis of smartphones with and without PCM over a specific timeframe revealed that, at a heating rate of 2°C per second, the temperature of components without PCM reached 55°C after 151 seconds. In contrast, with PCM, the temperature was significantly reduced to 48°C in the same period, staying below the critical threshold and preventing potential damage or performance degradation.

Overall, the study concluded that PCM significantly delays component heating by absorbing heat and undergoing a phase change, while efficiently transferring heat away from the components, leading to faster cooling and improved smartphone performance.

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