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Computational Study on Thermal Management of IC Chips with Phase Change Materials

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ABSTRACT

This paper introduces an implicit transient numerical formulation for a novel passive thermal management system designed to cool heterogeneous IC chips on a substrate board using minichannels. The design incorporates phase change materials (PCM) within minichannels placed around the IC chips' periphery. The PCM absorbs latent heat through direct conduction from the substrate board, facilitating its phase transition from solid to liquid, thereby enhancing the system's thermal cooling performance. The study evaluates three configurations: a system without PCM, a system with minichannel-coupled PCM, and an optimized single minichannel near the heat source. Additionally, the effectiveness of different PCMs, including paraffin wax, N-Eicosane, and ATP 78, is assessed. Results show that N-Eicosane PCM provides superior cooling, reducing the system temperature from 53.234°C in the generic model to 51.520°C. This represents a significant temperature drop of 1.714°C compared to the generic model, with additional reductions of 0.5°C and 1.35°C when compared to paraffin wax and ATP 78 PCM, respectively.

1. Introduction

The rapid expansion of the electronics industry and efforts to optimize space have led to smaller component sizes, resulting in increased heat generation and posing challenges to device reliability. Innovative cooling solutions are crucial for optimizing thermal management, which is essential for device performance and longevity, preventing failures due to elevated operational temperatures. This study focuses on evaluating the effectiveness of heat sinks in dissipating heat from IC chips, which is vital for maintaining optimal operating temperatures. By investigating heat sink-driven cooling strategies, this research aims to enhance the overall thermal management of integrated circuits. The study examines the cooling efficiency and potential temperature reduction achieved

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through the utilization of heat sinks, contributing to advancements in technology and ensuring the sustained performance and reliability of integrated circuitry in various applications.

Ramadhyani *et al.,* [1] conducted computational research on the conjugate heat transfer from small isothermal heat sources embedded in a large substrate, revealing that heat transmission is influenced by the substrate's thermal conductivity relative to the fluids. Faghri *et al.,* [2] analyzed turbulent flow in heated rectangular blocks using a modified Lam-Bremhorst turbulence model for high Reynolds number flow, finding that duct entry length reduces heat source leading-edge pressure drop. Culham *et al.,* [3] employed a Microelectronic Thermal Analyzer to predict local chip temperatures using a numerically coupled fluid-solid model with arbitrarily positioned heat sources. Chen and Liu [4] optimized the forced convection arrangement of nine heat sources, determining that center-to-center spacing optimizes heat transfer.

Chuang *et al.,* [5] numerically simulated heat transfer in five locations using PHOENICS, discovering that top heat sources had the highest temperatures in all configurations. Furukawa and Yang [6] used the SIMPLER numerical approach to solve the governing equations and found that increasing thermal conductivity via board thickness improves chip cooling and maximizes heat transfer at chip surfaces. Yadav and Kant [7] used the k-E model to study how array size and substrate temperature affect heat transfer rates from a heated module.

Baudoin *et al.,* [8] achieved optimized passive cooling of a source array flush-mounted on a vertical plate through natural convection, finding that vertical spacing must be nearly double horizontal spacing, with the ideal arrangement depending on heat source density. The staggered configuration developed by Baudoin *et al.,* [9] resulted from mathematically optimizing the placement of numerous power electronics components for cooling. Kurhade *et al.,* [10-12] conducted numerical studies on PCM cooling for smartphones and thermal performance, while Patil et al., [13], Waware et al., [14,15,29] provided critical reviews on heat transfer and enhancement in tubular heat exchangers with jet impingement.

Khot Rahul *et al.,* [16-21] investigated the impact of laser welding parameters on the strength of TRIP steel. Gadekar *et al.,* [22,24] conducted experimental studies on gear EP lubricant mixed with Al2O3/SiO2/ZrO2 composite additives to design a predictive system. Kamble *et al.,* [23] explained study on gearbox oil blended with composite additives. Patil *et al.,* [25] used a water-based Al2O3 nanofluid for grinding materials, citing its excellent convective heat transfer and thermal conductivity properties. Upadhe *et al.,* [26] explains water saving and hygienic faucet for public places in developing countries. Rosli *et al.,* [27] explained that varying mass flow rates resulted in overall efficiencies of 90.82%, 90.54%, 90.48%, and 90.46% for flow rates of 10kg/h, 30kg/h, 50kg/h, and 70kg/h, respectively. Additionally, solar irradiance levels of 200 W/m^2, 450 W/m^2, and 800 W/m^2 yielded overall efficiencies of 91.17%, 90.82%, and 90.33%, respectively. However, increased flow rates require stronger pumps, increasing system costs. Kurhade *et al.,* [28] discussed using a CFD approach for thermal management to enhance the reliability of IC chips. Li *et al.,* [30] explains CFD simulation of novel adaptive pin-fins microchannel heat sink to improve thermal management of electronic chips. Wang *et al.,* [31] found a prediction accuracy deviation of around 0.6 K and a correlation coefficient (R^2) near 1.

Phase Change Materials (PCMs) are essential for thermal energy storage, as they absorb and release significant latent heat during phase changes, usually between solid and liquid, at nearly constant temperatures. This enables effective temperature regulation, improved energy efficiency, and compact, lightweight storage. PCMs are used in building materials for temperature control, electronic devices for heat management, cold chain logistics for low-temperature maintenance, and renewable energy systems for energy storage. They come in organic, inorganic, and eutectic types, selected based on application requirements.

Most research has focused on PCM-based heat sinks, using experimental and numerical methods to study thermal conduction between PCM and heat-generating surfaces like IC chips. However, there is a notable research gap in the use of PCM-based minichannels for IC chip cooling. This study addresses this gap by investigating paraffin wax-based minichannels both numerically and experimentally. The goal is to optimize the heat dissipation of integrated circuit chips and improve their performance. The study utilizes IC chip and substrate board dimensions from the manufacturer's catalog to ensure an ideal configuration of seven IC chips on the board. The aim of this study is to address the research gap in PCM-based minichannels for IC chip cooling by investigating paraffin wax-based minichannels through numerical and experimental methods, with the goal of optimizing heat dissipation and improving the performance of integrated circuit chips.

2. Computational Approach

This study focuses on the numerical investigation of IC chips surrounded by minichannels. In numerical model original substrate board dimension is 269 X 189 X 5 as shown in Figure 1 and the material used is copper cladding. The setup consists of nine dissimilar IC chips placed on a substrate board, with minichannels filled with phase change material (PCM) encircling the IC chips. This configuration allows the PCM to absorb latent heat from the substrate board through direct conduction from the IC chips. The computational domain for the analysis was created using ANSYS Fluent software, version 2021 R2. The substrate board used in the numerical model has dimensions as depicted in Figure 1. The range of heat flux inputs to the dissimilar IC chips varies from 0.5 to 8 watts, as detailed in Table 1.

Transient numerical simulations for all scenarios were performed using the Solidification and Melting model in ANSYS Fluent V2021, incorporating enthalpy-porosity modeling with a mushy zone constant of $C=10^5$. This constant characterizes the heat transport properties of the PCM. The phase change materials used in the present analysis are classified based on their melting points, as shown in Table 2. The present analysis is carried using natural convection heat transfer mode with assignment of 5HTC at the wall of solid IC chips. 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 of IC chip. The pressure based is used as the entire simulation is based on the natural convection and conduction mode of heat transfer and the second order gradient momentum is used so that the accuracy and the preciseness of the solution is correct.

Table 1
Specification of heat source configuration

EC	L (mm)	W (mm)	H (mm)	Q-Watt
MP1 (U1)	35	35	4	9
MP2 (U2)	27	27	3	5.5
MP3 (U3)	15	15	4	3.75
IC4 (U4)	12.5	12.5	3	2
IC5 (U5)	19.65	6.5	3.43	2.5
IC6 (U6)	15	20	3.5	3
MF1 (U7)	12	20	3	3
MF2 (U8)	20	20	3	2
MF3 (U9)	20	20	3	1

Table 2
Thermophysical properties of PCM

Sl. No.	Property	Paraffin wax	n-Eicosane	ATP 78
1	Density, kg/m^3	748	778	756
2	Thermal conductivity, W/mK	0.26	0.25	0.26
3	Dynamic viscosity, Ns/m^2	1.856	0.01	0.01
4	Specific heat, J/kgK	2944	2455	2240
5	Latent heat of fusion, kJ/kg	264	238	220
6	Melting point, ◦C	48.28 - 54.21	35.5	76

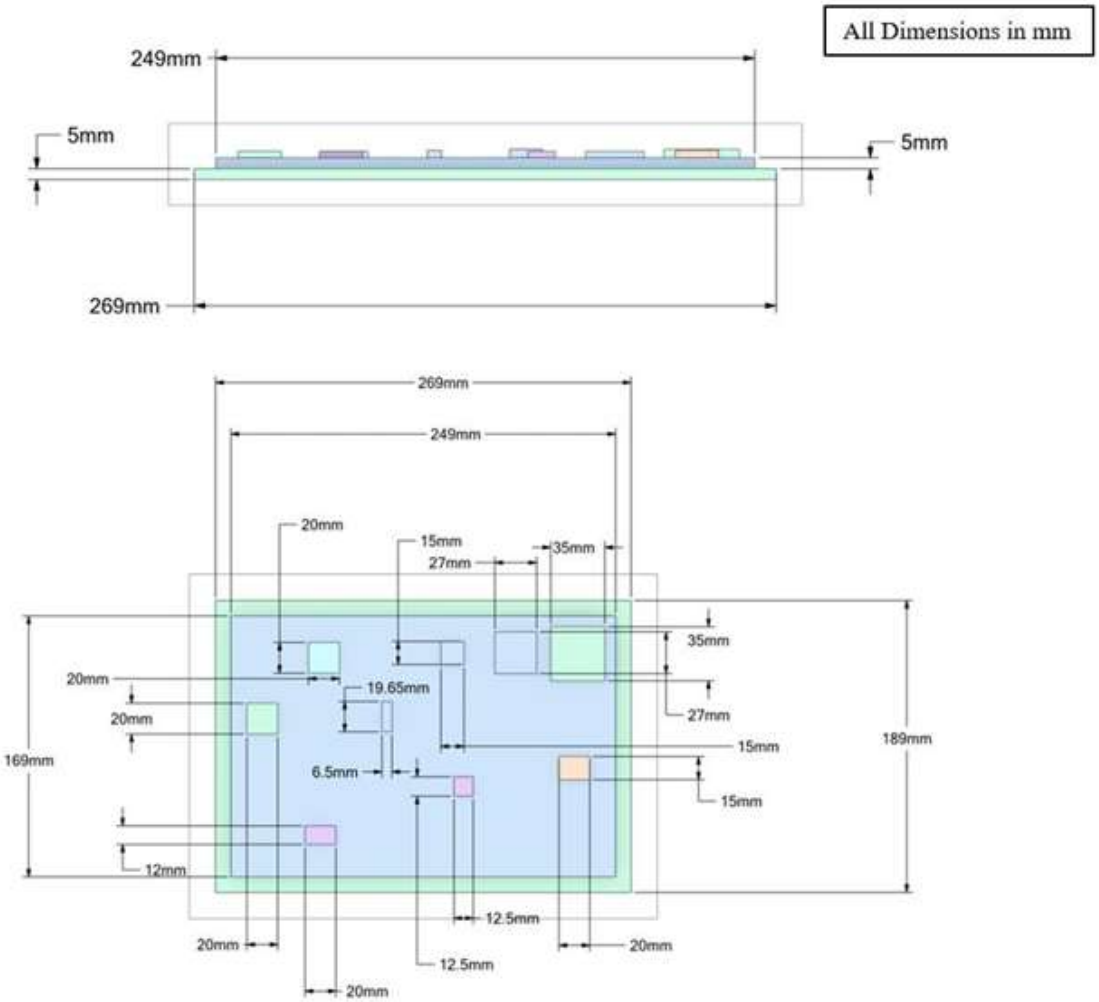

Fig. 1. Dimensional configuration

3. Boundary Conditions and Assumptions

The current analysis utilizes natural convection heat transfer, applying a heat transfer coefficient (HTC) of 5 at the walls of the solid IC chips. An adiabatic condition is established by setting the wall domain to an ambient temperature of 25°C during initialization.

i) A pressure-based setup was used, employing a bounded second-order gradient momentum method.
ii) The energy equation was activated to model the heat source for the IC chips.

iii) The solidification and melting model were activated to account for latent heat and the thermophysical properties of PCM during phase change, with a mushy zone constant of $C=10^5$ to represent the porosity behavior of the PCM.
iv) Radiation effects were neglected.
v) Conduction was considered the primary mode of heat transfer for the analysis.
vi) A heat transfer coefficient (HTC) of 5 was assigned to the solid walls to simulate natural convection behavior.
vii) An ambient temperature of 25°C was assigned to the walls during initialization to create an adiabatic domain in the setup.

These conditions and assumptions form the basis for the numerical investigation, aiming to provide a comprehensive understanding of the thermal performance of IC chips with PCM-filled minichannels. The governing equations are reported from researcher Kurhade et al., [28].

4. Result and Discussion

The current study concentrates on transient numerical simulations of a novel model featuring phase change material (PCM) integrated within minichannels. These PCMs, embedded within the minichannels, are employed to cool IC chips across various scenarios detailed in Table 2. The minichannels are affixed to the substrate board, facilitating phase transition through direct conduction with the PCM. The heat transfer process follows a specific pathway: from the integrated circuits to the substrate board, from the substrate board to the minichannels, and finally, from the minichannels to the PCM. This structured transmission mode ensures efficient cooling of the IC chips by leveraging the latent heat absorption capabilities of the PCM. Minichannel is surrounded around the periphery of IC chip. The intention behind this proposed design is to absorb maximum amount of heat generated from the heat source by means of direct conduction and reduce temperature across the system. The electronic components are mimicked with aluminum chip and the thermal conductivity of aluminum is considered.

4.1 Generic Model

In the generic model, passive cooling without minichannels or PCM is considered. The heat source at the IC chip is specified in Watts, as detailed in Table 1. Figure 2 illustrates the temperature contour for this configuration. The results show that at IC chip 1, where the temperature peaks at 53.234°C, heat propagates to nearby IC chips. To mitigate this thermal propagation and improve temperature control, a minichannel-coupled cooling method is introduced. This method aims to absorb the maximum amount of latent heat from the source and reduce the system temperature. Consequently, the configuration is modified to include PCM.

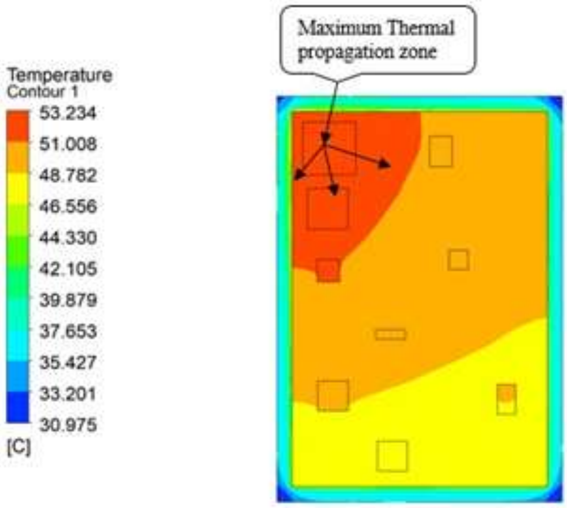

Fig. 2. Temperature contour

4.2 With Paraffin Wax Cooling

The results indicate, with paraffin wax poured minichannel cooling temperature is controlled to the 52.00^{0}C in present design. Figure 3 shows temperature contour for this configuration. Comparatively, it can be observed that thermal propagation from IC chip 1 to the adjacent IC chips is significantly reduced, leading to an optimal temperature distribution across the entire system. Referring to the liquid fraction contour depicted in Figure 3, it is evident that the maximum latent heat absorption occurs near IC chip 1, the primary source of thermal propagation. The liquid fraction rate near minichannel 1 is particularly high, indicating effective heat absorption at the junction of IC chips 1 and 2. This efficient absorption contributes to the overall thermal regulation within the system, ensuring that the heat generated by IC chip 1 is effectively managed and dissipated.

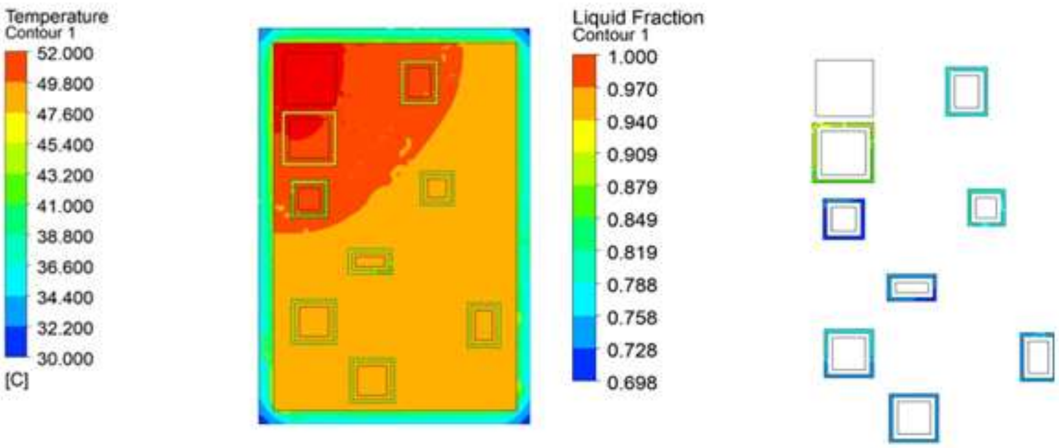

Fig. 3. Temp. & liquid fraction contour paraffin wax cooling

4.3 With ATP 78 Cooling

The ATP 78 PCM has a melting point of 78°C. The results show that ATP 78 PCM can reduce the temperature to 52.856°C in the current case. Figure 4 illustrates the temperature contour for this configuration. However, when compared to the minichannel model using paraffin wax, ATP 78 PCM does not provide as effective temperature control. During operation, at 3600 seconds, ATP 78 PCM exhibits a liquid fraction rate of 0.494 near the junction of the first minichannel, as shown in Figure 4. Due to its higher melting point, ATP 78 PCM is less effective at cooling, as it introduces a temperature delay effect in the system, reducing its overall cooling efficiency.

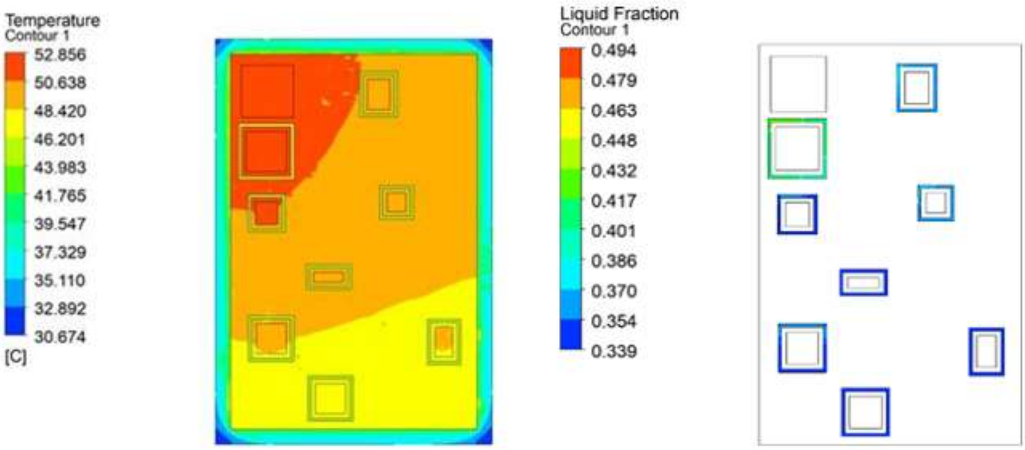

Fig. 4. Temperature & liquid fraction contour for ATP 78 cooling

4.4 With N-*Eicosane Cooling*

In the present case, the minichannel is filled with N-Eicosane PCM, which has a melting point of 36.5°C. Using N-Eicosane, the system's temperature is reduced to 51.520°C in the current model. This represents a significant temperature drop of 0.5°C reduction compared to paraffin wax PCM, and a 1.35°C reduction compared to ATP 78 PCM. Due to its lower melting point, N-Eicosane is more effective at reducing the junction temperature, providing greater latent heat storage capacity. However, N-Eicosane cannot maintain its latent heat over extended periods, transitioning entirely to the liquid phase at 3600 seconds.

In the current configuration, it is evident that minichannels filled with PCM can effectively reduce the junction temperature from the heat source, with N-Eicosane PCM offering superior cooling performance compared to other PCMs. However, the temperature contour plot in Figure 5 indicates that IC chips 1 and 2 are the primary sources of heat propagation. Therefore, in the next configuration, the system was studied with a single minichannel placed between IC chips 1 and 2 to optimize cooling efficiency.

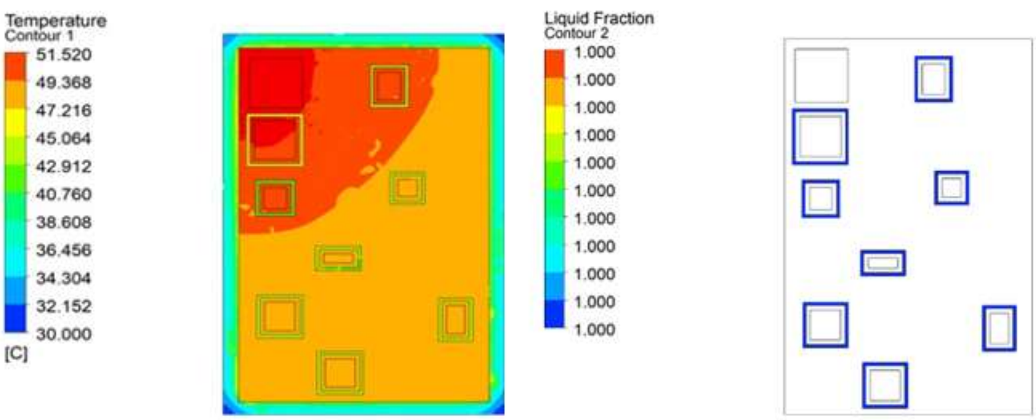

Fig. 5. Temperature & liquid fraction contour for N-Eicosane cooling

5. Results and Discussion

The numerical simulation of cooling for nine protruding IC chips mounted on an SMPS board involves employing phase change materials (PCM) with varying melting points within minichannels integrated into the board. The study explores nine different configurations of these minichannels and draws several key conclusions:

i) Phase change materials significantly contribute to reducing the temperature of IC chips, thereby enhancing their cooling efficiency.
ii) Comparative analysis between passive cooling without PCM and PCM-enhanced cooling demonstrates effective control over temperature and thermal propagation from the heat source using minichannel cooling.
iii) Direct submersion cooling presents several design constraints related to electronics packaging. In contrast, minichannel-coupled PCM cooling effectively reduces junction temperatures through direct conduction. The compact size of PCM-coupled minichannel designs allows for easy customization according to packaging requirements.
iv) Comparative results reveal that the use of N-Eicosane PCM in minichannels effectively reduces junction temperatures compared to other PCM options.
v) The use of N-Eicosane PCM reduces the system temperature from 53.234°C in the generic model to 51.520°C, marking a significant decrease of 1.714°C. Additionally, it provides a further reduction of 0.5°C compared to paraffin wax and 1.35°C compared to ATP 78 PCM.

Overall, this study underscores the importance of PCM-enhanced minichannel cooling for effectively managing IC chip temperatures, highlighting its potential for optimizing thermal management in electronics packaging.

The study on PCM-based cooling for IC chips has notable limitations, such as focusing solely on specific PCMs like paraffin wax, N-Eicosane, and ATP 78, potentially overlooking other effective materials. The numerical simulations are constrained by idealized assumptions, highlighting the need for experimental validation. Additionally, the research does not address long-term stability or thermal cycling effects on PCM performance, nor does it explore scalability to larger systems or integration challenges with existing IC designs. Future research should broaden the PCM selection, validate findings through experiments, investigate long-term performance, develop optimization algorithms, assess cost and manufacturing feasibility, explore adaptive cooling strategies, evaluate environmental impacts, and incorporate multi-physics modeling.

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