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# System-level Thermal Management and Reliability of Automotive Electronics: Goals and Opportunities in the Next Generation of Electric and Hybrid Electric Vehicles

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**ABSTRACT**

The reliable operation of electronic equipment is strongly related to the thermal and mechanical conditions it is exposed to during operation. In order to ensure a long lifetime of components, it is imperative that any electronic packaging design takes into careful consideration the appropriateness of various thermal management schemes and the application-specific requirements in order to keep temperatures within certain limits. The exact requirement varies with the application, and electronic packaging designs for automotive applications are at particular risk of failure due to the naturally harsh conditions it is exposed to. Electronic devices in vehicles have to be able to operate and survive at much higher temperatures than their consumer counterparts. While that has always been an issue, the rise of electric and hybrid electric vehicles (EVs and HEVs), combined with a desire to fit as much as possible into the smallest form factor, the challenge of removing enough heat from electronic devices in automotive vehicles is constantly evolving. This paper closely examines the new challenges in thermal management in various driving environments and aims to classify each existing cooling methods in terms of their performance. Drive schedules used by the Environmental Protection Agency (EPA) for emission and fuel economy testing are taken as examples of different realistic driving scenarios and their predicted thermal profiles are evaluated against various cooling methods, both active, passive or a combination of the two (hybrid). Particular focus is placed upon emerging solutions regarded to hold great potential, such as phase change materials (PCMs). Phase change materials have been regarded for some time as a means of transferring heat quickly away from the region with the electronic components. Phase change materials are widely regarded as a possible means of carrying out cooling in large scales from small areas, considering their advantages such as high latent heat of fusion, high specific heat, controllable temperature stability and small volume change during phase change, etc. They have already been utilized as a method of passive cooling in electronics in various ways, such as in heat spreaders and finned heat sinks. The

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applications, however, have been mostly for system-on-chip handheld devices, and their adoption in automotive power electronics, such as those used in traction inverters, has been much slower. A brief discussion is made on some of the potential areas of application and challenges relating to more widespread adoption of PCMs. Merits of some of the existing PCM based solutions for automotive electronics applications are also discussed, as are their drawbacks and modifications.

## INTRODUCTION

*Table 1. Cooling methods and associated effective heat transfer coefficient ranges*

| Cooling method | Type | Effective 'h' range ($kW/m^2.K$) |
|---|---|---|
| Air cooling [2] | Active | <0.7 |
| Heat pipe [3] | Passive | <14.08 |
| Immersion/boiling [4] | Active | 3.8-38.5 |
| Indirect fluid cooling (Single/double phase) [5] | Active | <73.2 |
| Spray cooling [6,7] | Active | <86.0 |
| Jet impingement [8] | Active | 5-96.2 |

There has been a dramatic shift in the requirements of electronics cooling in vehicles in the last two decades, with the advent of electric and hybrid electric vehicles. The most expensive electronic components in cars are no more stereos and speakers, but the powertrain electronics that are central to the propulsion of the vehicle. The semiconductor devices used in electrical power control systems, such as DC to AC inverters for electric motors and DC to DC converters for powering the accessories, can dissipate power in the range of tens of kilowatts [1]. Traditionally, air cooling has been used to cool the electronics in cars, but at high dissipation rates it is inadequate. One possible approach to cooling these semiconductor devices is to use engine coolant, previously cooled by the vehicle radiator, flowing through liquid cooled cold-plates. A major drawback with this approach is that it can add considerable cost, weight and volume to a hybrid vehicle drive system and hence there is a significant need for low-cost, high-performance cooling approaches. Table 1 shows some high-performance cooling methods that can be potentially investigated for such applications, along with a range of values of the convective heat transfer coefficient, h.

The major drawback of these methods, particularly those with the highest performances, is that they are for the most part, liquid-based active methods, requiring complex pumping and channeling networks, which adds to the cost and make them susceptible to failure. The use of phase change materials can be an interesting alternative in this situation. Phase change materials work by absorbing heat from the surroundings to first rise to its phase change temperature, then undergoes phase change at constant temperature while absorbing heat (fig.1). That way, heat continues to be taken in by the PCM, but without causing any temperature rise, at least until all the PCM are melted. In that situation, it has to be allowed to return to its original phase before being used again. Several phase change materials have been looked into, such as paraffin wax, sorbitol, *n*-eicosane, etc [9-11], and there have been successful attempts to improve their heat transfer characteristics [12]. Despite advancements, PCMs are yet to take off as a viable cooling solution for automotive applications, and studies into them has mostly looked at mobile and handheld device applications [13,14] This paper aims to make the case for the adoption of PCMs by highlighting its invaluable benefits that can be leveraged in ground transportation applications. It starts with a simple mathematical model that can be used to predict temperature profiles, which are then compared to cases where PCMs are not used. It is then shown how that leads to a marked improvement in reliability, both at the device and system levels

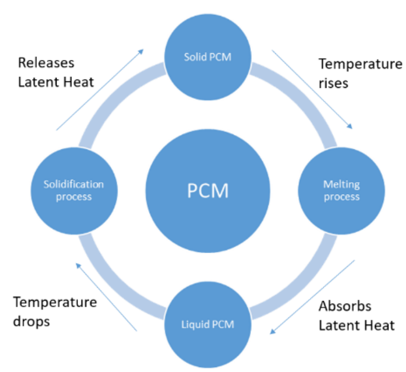


*Figure 1. Phase change process cycle*

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## MATHEMATICAL MODEL

A simple energy balance of the system consisting of a heat sink embedded with phase change materials can be formed as

$$\begin{aligned} &\textit{Heat dissipated at die} \\ &= \textit{Heat absorbed by heat sink and PCM} \\ &+ \textit{Energy lost by convection} \end{aligned}$$

$$Qdt = (m_1c_1 + m_2c_2)dT + hA_s(T - T_\infty)dt \quad \text{(i)}$$

where *m* and *c* are the mass and specific heat capacity, and indices 1 and 2 represent the materials of the heat sink and PCM, respectively, *h* is the convective heat transfer coefficient and $A_s$ is the surface area for convection. Assuming lumped mass in order to ensure the analysis is not more complex than needed, the transient temperature distribution of the heat sink-PCM system is given by

$$T = \frac{Q}{hA_s} - [\frac{Q}{hA_s} - (T_i - T_\infty)e^{-\frac{hA_s}{m_1c_1+m_2c_2}t}] \quad \text{(ii)}$$

The above equation is applicable for the system before the melting point of the PCM is reached. After that, the thermal energy causes phase change in the PCM at constant temperature. A similar type of energy balance approach during phase change (fusion when the PCM is solid at room temperatures) gives the mass of the PCM that has converted to liquid

$$m_L = \frac{[Q - hA_s(T_m - T_\infty)](t - t_m)}{\Delta H_{fusion}} \quad \text{(iii)}$$

Where $m_L$ is the mass of PCM that has undergone phase change, and $t_m$ is the time at which the phase change commenced.

A simple model of the HS-PCM system is created by solving the above equations numerically. Kandasamy, Wang and Mujumdar [15] carried out experimental work with paraffin wax as the PCM embedded in finned heat sinks. The results for the first of those heat sinks (HS1) with Q=2 W was compared to the model. The model shows considerable agreement with experimental results (fig. 2). The discrepancy in time to reach steady state is likely due to the simplifications introduced in the model, such as assumption of lumped mass and considering only convection through the heat sink and ignoring other losses. For steady state analysis purposes, the mathematical model is concluded to have sufficient accuracy for use as a tool for further analysis.

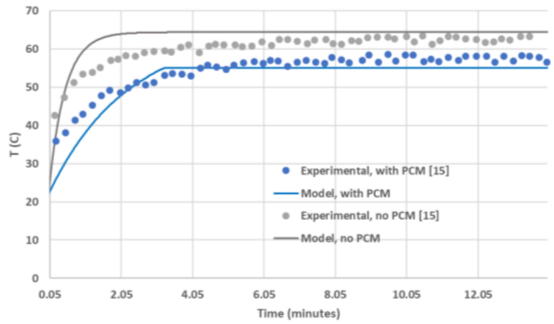


*Figure 2. Comparison of model with results obtained by Kandasamy et al. [15]*

## CIRCUIT MODEL

A circuit simulator can model the system incorporating phase change material accurately with a significant speedup compared to FEM thus it is suitable for use in the optimization loop. A system can be modeled as a compact thermal RC-network. To capture the change in heat absorption from one phase to another, the PCM can be modeled as a variable capacitor controlled by voltage or a switch. PCM has different specific heat value for solid and liquid phase, which is converted into two capacitance values respectively. To dynamically change the capacitance value of the PCM layer, voltage-controlled capacitor model is used. For the simple structure (shown in Fig. 3 (a)), corresponding encapsulant and PCM layer models are shown in Fig. 3 (b) and (c) respectively. In Table 2, thermal conductivity and dimension of the layers are shown. For the simulation setup, the ambient temperature is 20$^o$ C and the heat transfer coefficient is 1000 W/m$^2$-K (a sample h value of forced liquid cooling). Here, PCM has been modeled as a pair of a voltage-controlled variable resistor with a variable capacitor. The thermal network of the system is solved using HSPICE (a circuit simulator) and the results are shown in Fig. 4. From the result, it is clear that PCM has a high heat absorption capability at the melting point, which is 59º C in this case.

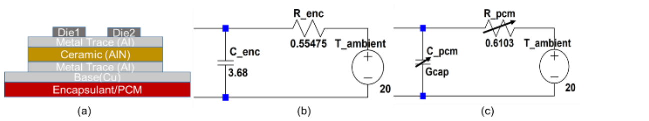


*Figure 3. (a) Cross-section of the structure (b) RC-network for encapsulant and (c) PCM*

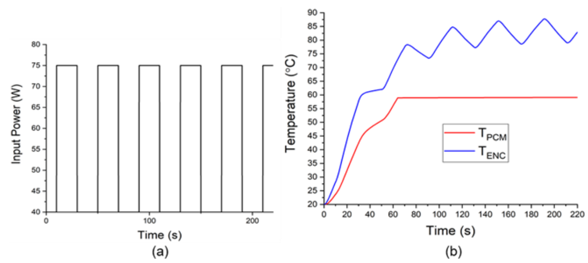


*Figure 4. (a) Input power waveform and (b) transient analysis result for PCM vs. encapsulant layer*

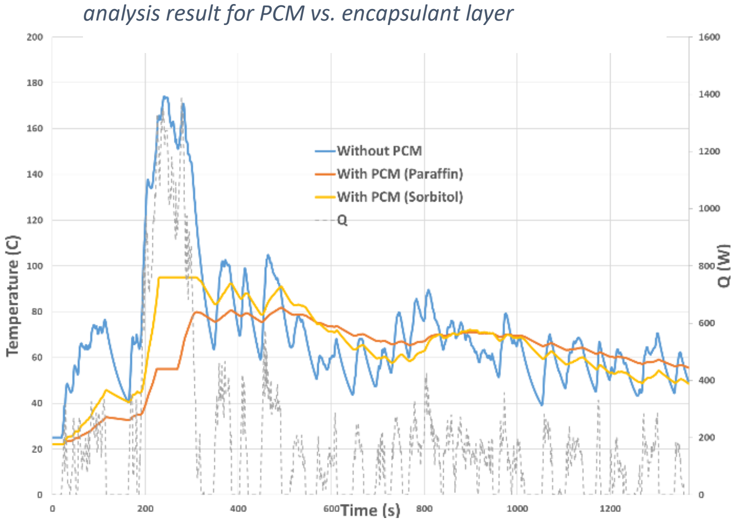


*Figure 5. Load (Q) and temperature profiles with and without PCM*

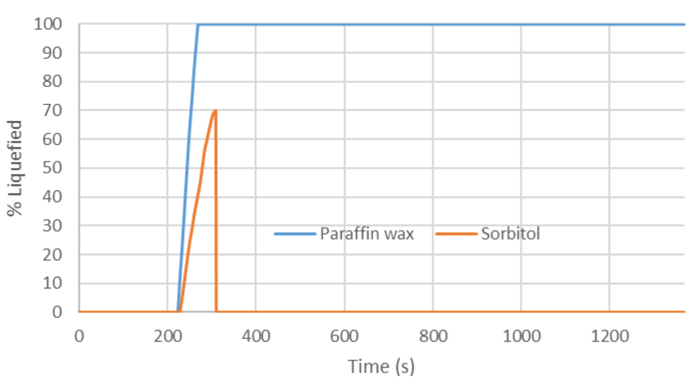


*Figure 6. Fraction of PCM liquefied*

*Table 2. Dimensions and thermal properties of the structure shown in Fig.2 (a)*

| Layer | Dimension (mm) | Thermal Conductivity (W/m-K |
|---|---|---|
| SiC (Die) | 4×4×0.5 | 120 |
| Trace (Al) | 30×30×1 | 172 |
| Ceramic (AlN) | 30×30×5 | 170 |
| Base (Cu) | 50×50×5 | 390 |
| Encapsulant | 50×50×1 | 3 |
| PCM (Metal) | 50×50×10 | 18.9-18.5 |

## THERMODYNAMIC ANALYSIS

Kandasamy's heat sink was aimed at system-on-chip applications, where the heat dissipation is at least two orders of magnitude smaller than what is seen in automotive applications. To account for this upscaling, a different heat sink was chosen, similar to the one described in a previous work by Nafis et al. [13]**.** The aluminum heat sink has ten rectangular fins with a base area of 0.012 m$^2$. The volumetric region in between the fins is taken to be half-filled by a PCM material. As sample use condition, a standard drive schedule used by EPA for fuel and emissions testing is used: the Urban Dynamometer Drive Schedule (UDDS), which simulates city driving behavior, with stop-and-go traffic. The drive schedules are used to build up a representative heat dissipation curve based on reasonable values of vehicle characteristics and efficiency of drivetrain electronics (fig. 5).

One of the primary advantages of using PCMs, as discussed previously, is its ability to absorb heat at a constant temperature. It results in a level of temperature control not found in other forms of thermal management. PCMs allow an effective upper limit on the design of the cooling system, which has implications for safety and reliability of the vehicle. Fig. compares the thermal profile obtained using a PCM-embedded heat sink with that of a more conventional heat sink studied previously by Nafis et al. The PCMs considered here are paraffin wax and sorbitol, with melting points of 55 ºC and 95 ºC respectively. A visual comparison points to a more consistent temperature profile in the system with PCM, with small fluctuations, a noteworthy improvement

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over a traditional, no-PCM heat sink. Table 1 highlights the salient differences between the cases. As expected, there is a 50-60% reduction in the extent of the temperature swing, a key parameter in reliability analysis. If the initial few seconds, where the device(s) heat up from ambient temperature, were excluded, the difference would have been even more significant.

*Table 3. Temperature profile characteristics with no PCM, paraffin and sorbitol*

| Parameter | No PCM | Paraffin Wax | Sorbitol |
|---|---|---|---|
| Maximum temperature | 174 | 82 | 95 |
| Mean temperature | 99 | 52 | 59 |
| Temperatur e swing | 149 | 60 | 73 |

One major, if not potentially catastrophic, drawback of PCM is that it has a finite heat capacity, and when all the PCM has undergone phase change, any amount of power dissipation can lead to a rapid temperature rise. It is therefore important to track the amount of PCM that has already undergone phase change at any given time. In situations of constant temperature phase changes, the mass, or mass fraction of the two phases, can act as a thermodynamic indicator. The liquid fraction curve (fig. 6) shows the fraction melted to peak at 100 % for paraffin and 70 % for sorbitol. As paraffin changes phase at a lower temperature, it is completely liquefied. In order to keep this fraction lower, the engineer must consider a different PCM material with higher specific heat, or a larger volume of the same PCM material. The latter adds more weight and cost, while the former may be limited by availability, cost and technology.

## RELIABILITY CONSIDERATIONS

Reliability of the electronic equipment is a critical consideration in designing a thermal management scheme. The application of PCM hold great promise in this regard by mitigating some of the key failure drivers. This brief analysis looks at two different aspects of the reliability approaches to a vehicle's cooling system with PCM incorporated: device-level reliability and system-level reliability. The system level reliability discusses some of the tradeoffs in a cooling system with PCM as well as an active, more traditional cooling loop.

## DEVICE LEVEL RELIABILITY

Reliability of devices under operational or extreme conditions is often dictated by the highest risk failure modes, as it is often seen that the same failure causes the device to malfunction. Interconnects are often such a risk area, due both to the regularity and criticality of interconnect failure. For example, an attempt to study the reliability of insulated-gate bipolar transistors (IGBT) devices for traction applications consistently found the first failure to be always at the aluminum wire bonds, an interconnection often used in electronic packaging **[18].** Here an attempt is made to use the model developed in that study to quantify the relative risk, and its potential risk reduction when using a PCM. As the wirebonds were always the first to fail, the model should apply to other types of modules, such as MOSFETs, that use aluminum wire bonds.

The lifetime correlation of an IGBT was developed by Held et al.(19), given by

$$N_L = A(\Delta T)^{-5} e^{-\frac{E_A}{kT}} \qquad \text{(iv)}$$

Where $N_L$ is the number of cycles to failure, $\Delta T$ is the temperature swing and $T$ is the medium temperature. For aluminum wirebonds, A=6400, $E_A$= 78000 J, and $k$ is the Boltzman constant. Using this expression, the relative acceleration factor for a case of no PCM is found to be in the order of 460, i.e. for 1 cycle that the device survives using a traditional, non-PCM heat sink, the device would survive 460 cycles paraffin PCM is used (fig. 7). While this is an analytical estimate made with assumptions, and considers only a single drive

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schedule, the size of the acceleration factor speaks to the potential of PCM-integrated cooling systems.

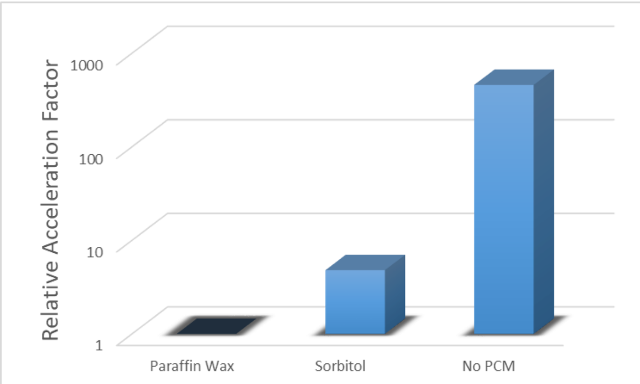


*Figure 7. Relative acceleration factors*

## SYSTEM LEVEL RELIABILITY

In order to assess the reliability of the entire cooling system, a simple risk profile is estimated. Without availability of statistical failure data from the field, the risks are assigned weights depending on severity and predicted failure frequency. The case considered is where a PCM based heat sink is paired with an active forced air cooling system. In such a scenario, the PCM-based cooling system is assigned a frequency value of one, the lowest possible value, on a scale of five, whereas a fan cooling system is assigned a value of three, as it is an active system with moving parts and therefore more susceptible to failure through wear out or electrical malfunction. The severity values are assigned according to the cooling load each is expected to carry. For example, in a situation where the PCM is designed to carry out 40% of the cooling, it is assigned a severity index of two, while the fan is assigned three, as shown in the table.

*Table 4. Sample risk table for system risk assessment comparison between PCM (passive) and fan (active) cooling schemes*

| Component | Frequency | Severity | total |
|---|---|---|---|
| PCM | 1 | 2 | 2 |
| Fan | 3 | 3 | 9 |

The total risk index for each device is the product of its failure severity and frequency. The device risks are then summed up to assign a system risk index. A risk curve can be drawn up relating the fraction of load carried by the PCM against total system risk (fig. 8).

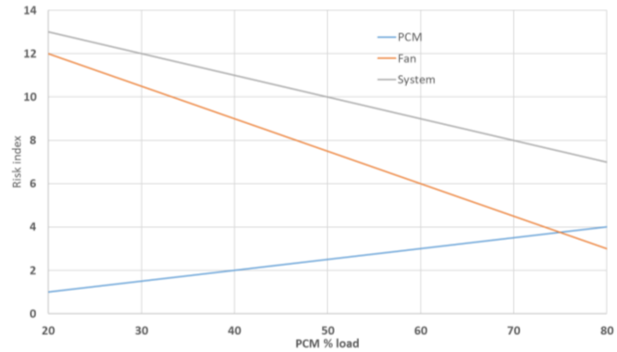


*Figure 8. Device and system risk*

The risk curve suggests a lower overall risk if higher loads are being carried by the PCM, but using a single cooling scheme is not recommended as it can lead to total system failure in case of some unforeseen event. In case of PCM, for example, there may be a situation where all the PCM has already reached liquid state, which essentially deactivates it as a cooling mechanism. In such a case, the active cooling scheme may dissipate at least some heat away, which can significantly prolong useful life of the electronic components. Other situations may involve PCM degradation, leakages in PCM container, and a host of other scenarios which the above risk quantification does not account for.

## CHOOSING THE RIGHT COOLING SYSTEM

If PCMs are available, the engineer in charge of designing a vehicle's cooling system will have to make critical decisions regarding the ratio of cooling load shared between the PCM and a more conventional active cooling system, such as  a fan. If the system is designed with a smaller fan, a greater mass of PCM must be stored, which adds weight to the vehicle. A properly optimized system would ensure that a large fraction of the PCM is liquefied during operation, as that implies energy being stored as latent heat. In theory, the higher the mass of the PCM packed into the cooling system, the more heat it can store, but in reality a large amount of PCM would add significant weight to the vehicle. Hence, the mass of the PCM, along with operating environment, would be the most important factor in choosing the appropriate fan size. A larger fan size would be able to carry away more heat, but besides adding more weight, it will also draw more power from the vehicle's power plant. The decision thus boils down

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to one between a more passive system (more PCM, lower fan power) and a more active system (more fan power). For example, Table 5 compares the temperature difference in a system with the same PCM but different values of h. For forced convection, a larger h would require a greater mass flow rate, and thus more fan power. The results imply a diminishing return on increased mass flow. Similarly, a greater PCM mass would mean more time required for conduction of the heat throughout the material, which again highlights the importance of optimization.

*Table 5. Difference between maximum and minimum temperatures at different convective heat transfer coefficients ($W/m^2K$)*

| | |
|---|---|
| h=60 | 59 C |
| h=200 | 38 C |
| h=340 | 33 C |

## DISCUSSION AND CONCLUSION

Phase change materials are a promising method of cooling electronics. They can help to ensure a more consistent temperature profile by mitigating the peaks by undergoing constant temperature phase changes. They can also facilitate an extra level of control to the thermal engineer as the PCM works like a constant temperature heat sink. Research on PCMs until now have largely focused on consumer electronics, such as mobile devices, but it can bring the same advantages to automotive cooling. Using a simple model to simulate transient temperature distribution, it was shown that using a PCM such as paraffin wax can lead to a much more consistent temperature profile with lower peaks and smaller temperature swings. This in turn can lead to a significant enhancement in useful life of an automotive electronic device. The model used, however, was fairly simple, and the effects such as non-uniform temperature distribution was not considered. However, it did agree with published experimental data on a small scale and can be concluded to be accurate enough for comparative analyses.

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