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Thermal Management of On-Board Chargers: A Review of Literature

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ABSTRACT

The continuous expansion of the electric vehicle (EV) market has led to higher power densities in electronic components, particularly in On-Board Chargers (OBCs). This increase presents significant thermal management challenges that directly affect efficiency, reliability, and cost. This paper provides a comprehensive review of recent literature on thermal management strategies for OBC systems, emphasizing cooling techniques, modeling approaches, and performance optimization. Various cooling methods—such as air cooling, liquid cooling, phase-change materials, thermoelectric cooling, and refrigeration-based systems—are evaluated in terms of heat flux capacity, cost, and practical applicability. The review also highlights the role of computational fluid dynamics (CFD), system-level modeling, and experimental analysis in designing efficient thermal systems. Findings indicate that liquid cooling remains the most effective and cost-balanced solution for high-density OBC applications, while hybrid and emerging technologies, including phase-change and thermoelectric systems, offer promising avenues for improvement. The study concludes that integrating electrical and thermal design from early development stages, supported by AI-driven optimization, can significantly enhance OBC performance, reliability, and energy efficiency.

1. INTRODUCTION

This review provides a comprehensive and up-to-date synthesis of thermal management strategies for On-Board Chargers (OBCs) in electric vehicles (EVs), integrating findings from both classical and recent studies up to 2025. Unlike previous reviews that focused on individual cooling methods or isolated components, this work presents a comparative analysis of multiple cooling techniques—including air, liquid, phase change, thermoelectric, and refrigeration-based systems—highlighting their heat flux capacities, cost implications, and design challenges within the same framework.

The study also introduces a systematic classification of thermal modeling approaches—system-level modeling, CFD simulations, and experimental validation—demonstrating how each contributes to optimizing OBC performance. Moreover, it emphasizes the synergy between electrical and thermal design and identifies how AI-assisted optimization can enhance design efficiency and cost-effectiveness.

In summary, the novelty of this study lies in its integrated evaluation of cooling technologies, modeling methodologies, and cost-performance trade-offs, offering a holistic reference for future OBC thermal management design in high-power, compact EV systems.

This work is a comprehensive literature review focused on the thermal management of OBCs used in EVs. The review systematically examines the evolution, principles, and performance of various cooling techniques applied to OBC systems, including air cooling, liquid cooling, phase-change materials (PCM), thermoelectric cooling, and refrigeration-based systems.

The scope of the study extends beyond a descriptive summary by incorporating a comparative analysis of these techniques in terms of thermal efficiency, cost-effectiveness, power density, and practical applicability. Additionally, the review explores thermal modeling and simulation approaches—covering system-level modeling, computational fluid dynamics (CFD) analysis, and experimental validation—to highlight best practices in OBC design and testing.

By integrating findings from recent research (2000–2025), the study provides a holistic overview of current challenges, technological trends, and emerging solutions in high-density power electronics cooling, serving as a reference framework for future OBC development and optimization.

2. EV OBC THERMAL MANAGEMENT OVERVIEW

The EV market has experienced rapid growth over the past decade, as shown in Figure 1 [1], driven by global efforts to reduce greenhouse gas emissions, improve energy efficiency, and decrease dependence on fossil fuels.

The OBC is a critical subsystem in the EV, responsible for converting alternating current (AC) from external charging sources into Direct Current (DC) suitable for charging the high-voltage battery pack. It serves as the primary interface between the grid and the vehicle's accumulator, determining not only the charging speed and efficiency but also the overall convenience and safety of the charging process.

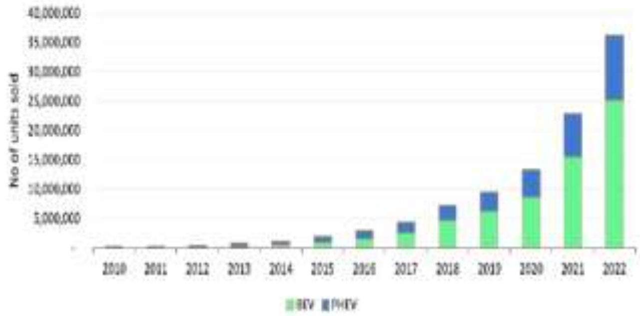


Figure 1. EV market trend

To further improve the overall system efficiency, new OBC architectures are made to be bi-directional, enabling grid-to-vehicle (G2V), Vehicle-to-grid (V2G), and vehicle-to-home (V2H), where energy can flow to or from the vehicle back to the grid or local loads, enhancing grid stability and energy flexibility.

As power density requirements in any power electronic devices increase, as shown in Figure 2, there is a constant push to minimize power losses, weight, and cost as much as possible. To accomplish this, the automotive industry implements high-power electronic devices in a wide variety of electronic packages. One of the typical examples will be Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET), which will be focused on in this literature. As the power density demands increase, so do thermal management requirements, as it is often the bottleneck that prevents an increase in power output for electronic packages.

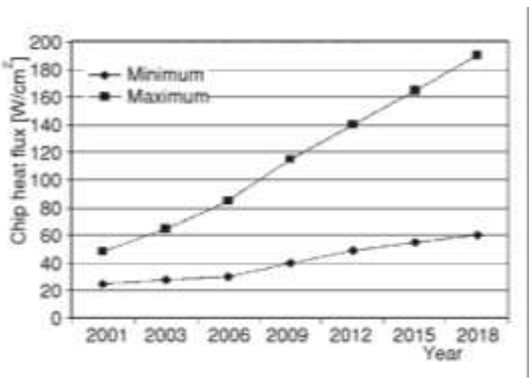


Figure 2. Heat loads increase over the years

The thermal management system employed will primarily depend on the packaging constraints and power dissipation. Natural convection can provide sufficient cooling, and it would be ideal since it would have the fewest mechanical components and no risks of leakage. If natural convection cannot keep the junction temperature requirements, then forced air convection can be the second-best option, but, in many cases, forced convection will require a large surface area that will affect power density requirements. One of the best techniques and that is widely used in the Automotive industry is liquid cooling, as it combines cost effectiveness and delivering required junction temperatures, although it has some drawbacks as leakage problems, and many components are required to achieve the goal as a cold plate, pump, heat sink, etc. It is still the best option so far for such applications. There are new technologies used, like PCMs and thermoelectric coolers. Each technique has its own pros and cons.

Thermal management is a key player in any electronic packaging. Though there are new techniques employed for cooling, the driving force in designing a thermal management system is the cost. Therefore, the technology used must be cost-effective and still deliver the system requirements.

3. HEAT GENERATION MECHANISM

3.1 MOSFET

In OBCs, the main component that generates heat and needs precise thermal management is the MOSFET, shown in Figure 3, as it controls the conversion of electrical energy through rapid switching. MOSFETs typically have two major heat generation sources, which are conduction and switching losses, both of which significantly affect the efficiency of the OBC.

Figure 3. SiC MOSFET

3.1.1 Conduction losses

It occurs during the "on" state of the device, when current flows through its channel. These losses can simply be calculated using the following Eq. (1):

$$P_{conduction} = I^2 R_{DS} \tag{1}$$

where, R_{DS} is the drain-to-source on-state resistance. In Silicon Carbide (SiC) MOSFETs, this resistance is relatively low and offers higher thermal conductivity, leading to reduced conduction losses and improved performance under high operating temperatures.

3.1.2 Switching losses

Switching losses occur during the transitions between the "on" and "off" states, when both voltage and current coexist across the device for a short duration. The total switching loss per cycle can be represented from Eq. (2):

$$E_{sw} = E_{on} + E_{off} \tag{2}$$

where, E_{on} and E_{off} are the energy (in joules) generated per cycle during turning on or off. The corresponding power loss can be calculated by Eq. (3):

$$P_{sw} = f \, x \, E_{sw} \tag{3}$$

where, f is the switching frequency.

In MOSFETs, the semiconductor die (the actual chip inside the package) is the primary source of heat generation (shown in Figure 4).

Figure 4. Die assembly inside the MOSFET

The conduction and switching losses occur directly within the die. However, in many cases, the inside design of a MOSFET is not accessible to thermal engineers due to confidentiality. Instead, the manufacturer gives junction-to-case thermal resistance. With the losses and case temperature known, the junction temperature can be easily calculated using Eq. (4):

$$P_{losses} = \frac{T_J - T_c}{R_{JC}} \quad (4)$$

where, P_{losses} is the total losses from the component, T_J is the junction temperature, T_c is the case temperature, and R_{JC} is the junction-to-case thermal resistance provided by the manufacturer.

3.2 Magnetics and capacitors

Beyond the MOSFET, other components in the OBC contribute significantly to the total thermal load. Magnetic components, such as the inductor, generate heat primarily through core losses and winding losses. Similarly, capacitors experience power dissipation due to equivalent series resistance, which converts current ripple into dissipated heat.

While the heat generation mechanisms in these components are different from the mechanisms of the MOSFET, their thermal management is also critical. They are usually cooled using the same heat sink used for cooling the MOSFET.

4. COOLING TECHNIQUES

Thermal management, in general, is classified into active cooling and passive cooling. Active cooling offers high cooling capacity and can even achieve junction temperatures lower than ambient temperature. Passive cooling systems include heat spreaders to the electronic package, effectively increasing the heat transfer area to decrease junction temperature. Figure 5 [2] compares different cooling techniques according to the junction temperature that can be achieved with respect to the applied heat flux.

There are many cooling techniques available in the market, and many are still in development. In this literature review, the cooling techniques to be discussed are:

- Air cooling
- Liquid cooling
- PCM
- Refrigeration cooling

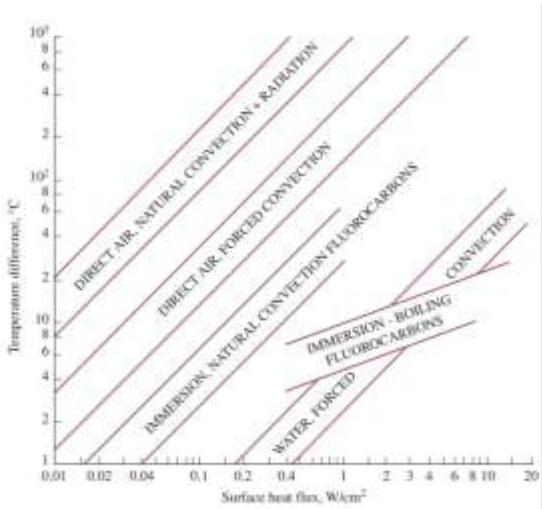


Figure 5. Comparison of different cooling techniques performance

4.1 Air cooling

The simplest, yet effective method for thermal management is most widely used in many applications ranging from small portable electronics to large-scale systems [3].

4.1.1 Natural convection

Natural convection is the most desired system for cooling because of its simplicity. Electronic boards that dissipate small amounts of heat and have relatively large surface areas can be effectively cooled by this method.

In many cases, natural convection as it is would not be useful for many applications; many techniques are used by changing fins orientation, dimensions, and materials to increase natural convection efficiency [3].

4.1.2 Forced convection

In many cases, natural convection cooling is not adequate for electronics packaging cases; forced convection is provided by using fans, pumps, jets, etc. Forced convection is a very popular case in electronics cooling combined with heat sinks (fins). Bharathan and Kelly [4] forced convection with finned heat sinks can meet the required thermal goals while keeping relatively low cost, but still did not solve the power density problem due to large heat sink surface area and large fans required in order to dissipate heat as compared to liquid cooling.

It is shown from Table 1 [4] that to dissipate the same amount of heat, we need nearly twice the volume of a liquid cooling system.

Table 1. Comparison between air and liquid cooling

Quantity	Air Cooling	Liquid Cooling
System mass (kg)	1.4	3.8
Volume (cc)	7000	3800
Parasitic power (W)	80	28
Relative component and system fabricated costs ($)	48	78

Many heat sink designs are available, while forced air cooling is the used method, but the main parameters to look for while designing a forced convection system are the pressure drop, manufacturability, and cost effectiveness of the cooling system. Bünnagel et al. [5] have introduced a new inlet criterion for further enhancing fin efficiency and increasing power density while keeping the design cost-effective and as shown in Figure 6.

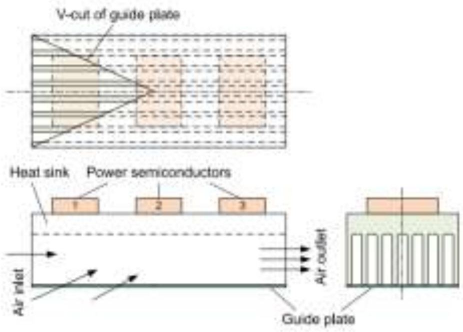


Figure 6. Air-cooling system assembly

The efficiency and power density of the package can be increased significantly when combining forced air cooling with liquid cooling. Casano and Piva [6] have proposed a novel way of creating a closed package, having a liquid cooling plate underneath the heat-dissipating components, and dissipating this heat using a plate fin-fan assembly that further enhances the power density while keeping operating conditions requirements. It can be shown in Figure 7.

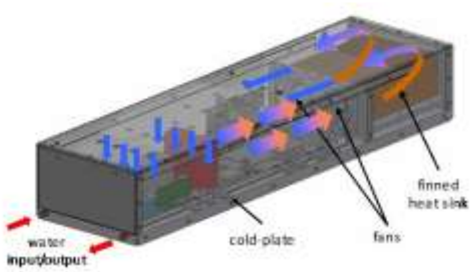


Figure 7. Combined air-liquid cooling system

4.2 Liquid cooling

In most cooling applications, the coolant used in the cooling system is water with some additives. In general, water has a specific heat that is 4 times that of air, allowing for higher power density, lower junction temperatures, and overall better cooling efficiency. The problems related to liquid cooling, such as leakage, corrosion, and increased weight, make this cooling technique used for applications that have very high heat fluxes and require high power densities that cannot be achieved by forced air cooling.

Liquid cooling itself has many techniques; the most commonly used technique for liquid cooling is putting cooling plates underneath the heat-dissipating component. Cooling plates have many shapes and have so many parameters that can be controlled to obtain the optimum cooling performance.

Vangoolen [7] talked about the different designs of liquid cold plates and explained how the size of the cooling paths, manufacturing, topology optimization, and electronics package mounting affect the behavior of the cold plate. He also explained how sealing techniques can be chosen based on the type of cooling plate.

Zhan et al. [8] have proposed new novel shapes for the serpentine-type cold plate that can lead to the development of a new structure. The author focused mainly on topology optimization without taking into consideration either the manufacturing methodology or the cost of the proposed designs.

Zou et al. [9] have proposed the effect of the number of flow channels in series and parallel configurations on both the pressure drop and the junction temperature. Chen and Wang [10] have proposed a newer technique for cold plates that contain microchannels. They also derived a relation between the friction coefficient, aspect ratio, and heat transfer coefficients can be shown in Figure 8.

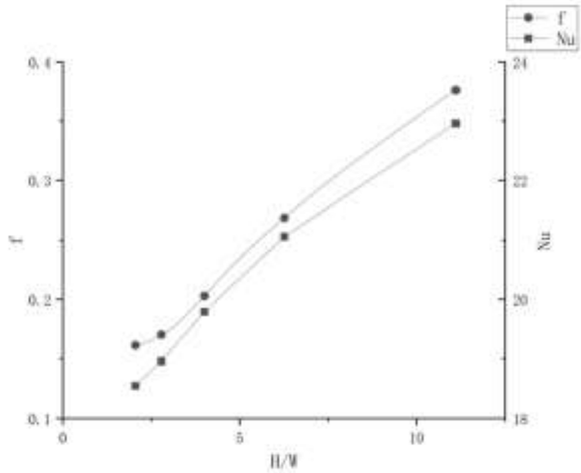


Figure 8. Effect of cold plate parameters on heat transfer coefficient and pressure drop

Some cold plate assemblies can be shown in Figure 9 and Figure 10. More cold plate assemblies and configurations are presented by Vangoolen [7].

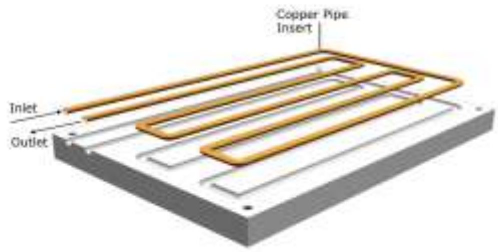


Figure 9. Formed tube cold plate

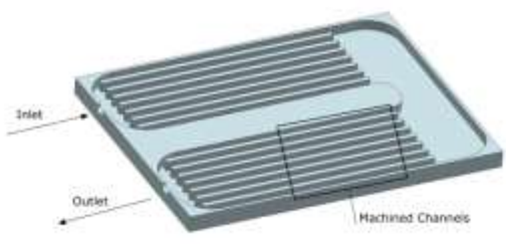


Figure 10. Mini channel cold plate

Akbarzadeh et al. [11] have also created a new type of liquid cooling by using a U-shaped cooling plate mounted as a jacket on the battery pack, as shown in Figure 11. This design is found to be the most efficient design from the power density POV, but it consumes high power due to the high pressure drop.

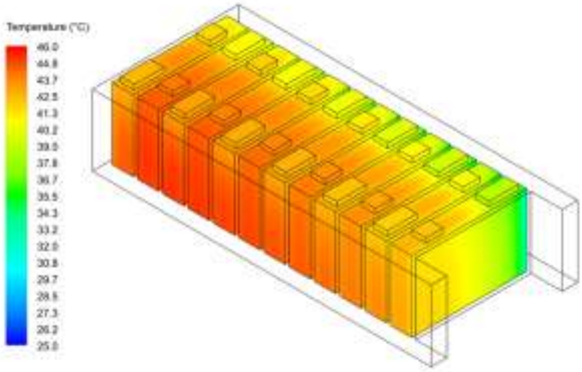
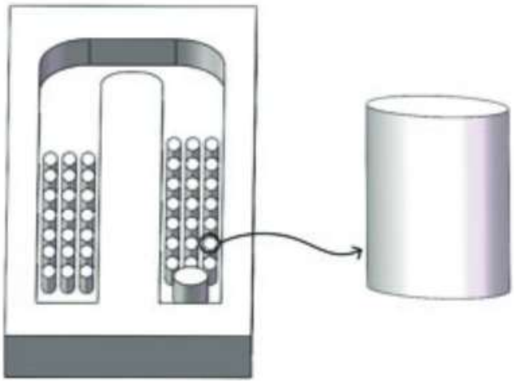
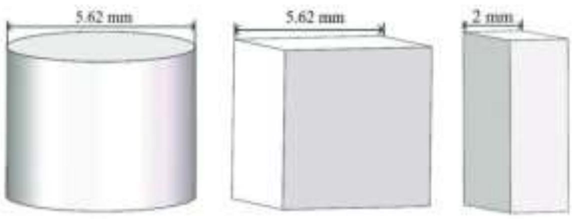


Figure 11. Battery pack U-shaped liquid cooling

Hu and Zhang [12] have also used the U-shaped liquid cooling technique for the batteries, but optimized the path with extended surfaces to improve fluid mixing and increase heat transfer performance, as shown in Figure 12.



(a) U-shaped liquid cooling model



(b) Internal fins have different structures

Figure 12. Improved U-shaped liquid cooling

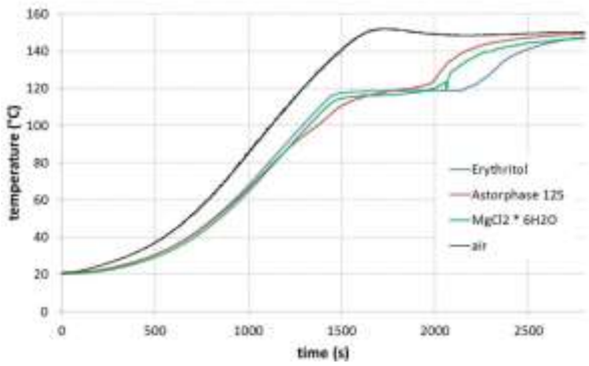
4.3 PCM cooling

PCM is widely used in electronic packages, starting from Laptops and batteries, up to rocket applications. PCM has many types and shapes according to the application. The most widely used type of PCM is heat pipes. The power of PCM is that it can take a specific amount of heat and keep its temperature constant, which is mostly used in applications that operate for a range of time with a specified load and then shut down.

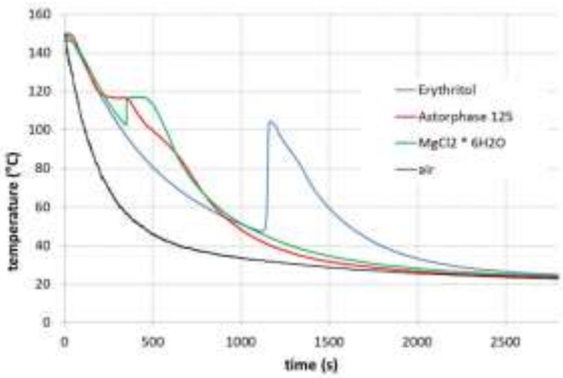
Septiadi et al. [13] have used heat pipes to cool EV batteries, shown in Figure 13, to test the efficiency of this procedure under different C rates. The authors proved the efficiency of this cooling system, but the problem with its use is that it needs to be cooled to its operating temperature before using it for the required load.

Figure 13. Battery pack PCM cooling

Novikov et al. [14] have compared many PCMs and used some of them to examine the thermal behavior of electronic assemblies. The investigation found that using PCM for electronics can be a good technique, but it depends entirely on the ambient operating conditions. Figure 14 shows the typical behavior of PCM for a given heating/cooling cycle [14].



(a) PCM heating curves



(b) PCM cooling curves

Figure 14. Different PCM materials behaviour

4.4 Refrigeration cooling

Refrigeration cooling is a newly developed way that is used in modern EVs when the ambient conditions are harsh enough to make any other cooling method inefficient. Refrigeration cooling is normally combined with air or liquid cooling systems to enhance efficiency. It is a proven thermally efficient cooling system, but its problem is mainly its cost due to more design complexity and high-power consumption.

Chiriac and Chiriac [15] have used a refrigeration system as a standalone cooling system for electronics; it proved its reliability, but it has a very high cost compared to liquid cooling, which could give the same performance with less initial and running cost.

Another way that can be called refrigeration cooling is thermoelectric cooling using the so-called Peltier modules. It is a method that uses the Peltier effect to move heat from one side to another side by applying voltage to the module terminals. It is a method widely used in electronics cooling.

Lakhkar et al. [16] have investigated the feasibility of using thermoelectric cooling as a thermal management system for a computer processor. The thermoelectric cooler has proved its ability to cool down the processor temperatures even below the ambient temperature.

This method is optimum used for computer processors as the available thermoelectric coolers in the industry are of specific dimensions, which makes it hard to use for a wide range of applications. In addition, thermoelectric coolers consume too much power, which decreases the overall system efficiency, and they are always in need of a large heat sink to dissipate the power lost by the module [17].

According to the details and references mentioned, the optimum cooling solution can be selected based on Table 2 as follows:

Table 2. Cooling techniques comparison

Cooling Technique	Heat Flux Capability (W/cm²)	Power Density Gain	Cost (Relative)
Natural Convection	<5	Low	Lowest
Forced Convection	5–20	Medium	Low
Liquid Cooling	20–100+	High	Medium
PCM	10–50	Medium – high	Medium
Refrigeration	>100	Highest	Highest

5. THERMAL MODELING AND SIMULATION APPROACHES

In order to quantify the system performance, we need to test it. The testing of the designed system can be made using one of 3 ways. System-level modeling, CFD approach, and experimental analysis.

5.1 System-level modeling

Since the MOSFET is the major component that dissipates heat in this specific application, the lumped parameter model for this system can only have MOSFETS without taking into consideration the other heat-dissipating components.

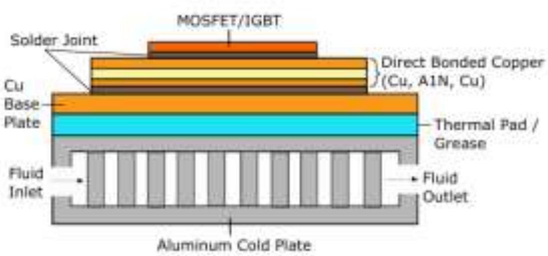


Figure 15. Typical electronic cooling assembly

Figure 15 shows the typical setup of the MOSFET cooling assembly. Since the die (heat-generating part in the MOSFET) is very small and the overall dimensions of the MOSFET are relatively small, it can be assumed to be a 1-D thermal problem with the thermal circuit shown in Figure 16:

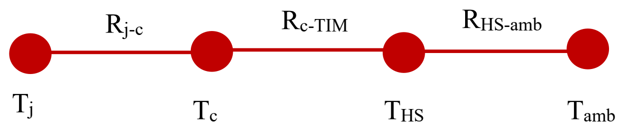


Figure 16. MOSFET thermal network

where,
T_j is the junction temperature, T_c is the case temperature, T_{HS} is the heat sink average temperature, and T_{amb} is the ambient temperature.
R_{j-c} is the junction-to-case thermal resistance (provided by the manufacturer), R_{c-TIM} is the thermal resistance of the thermal interface material, and R_{HS-amb} is the thermal resistance of the heat sink to ambient.

To predict the transient behavior of an electronic component as the MOSFET, a circuit as a Foster network, shown in Figure 17, or a Cauer network, shown in Figure 18, is used. Dini and Saponara [18] have proposed a system-level model for MOSFETs to capture the behavior under transient conditions using the Foster thermal network. The authors' model is made to capture the behavior under the worst-case conditions and to also capture some electrical parameters that will help design the overall board and ensure that thermal vias are placed in the correct place. They did not dive deep into the thermal model, but only the transient analysis to get peak temperatures. Orr et al. [19] have also used transient modeling for an inverter heat sink to predict its behavior.

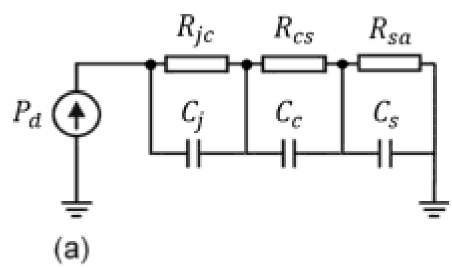


Figure 17. Foster thermal network for transient analysis

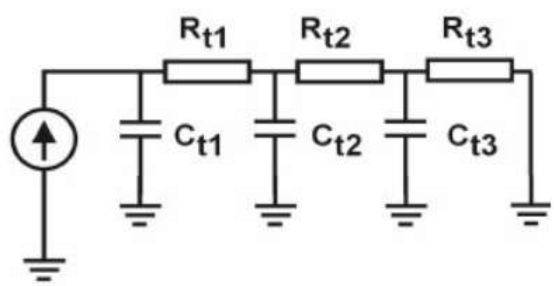


Figure 18. Cauer thermal network for transient analysis

Wang et al. [20] have proposed system-level modeling of the overall cooling system, taking into consideration the cooling plate, pump, heat sink, and heat source. The author used this modeling method due to the system complexity, as it contained a normal liquid cooling system combined with an air refrigeration system, shown in Figure 19. The author used this model to identify the temperature of the batteries when the air conditioner is off and at different pumping flow rates.

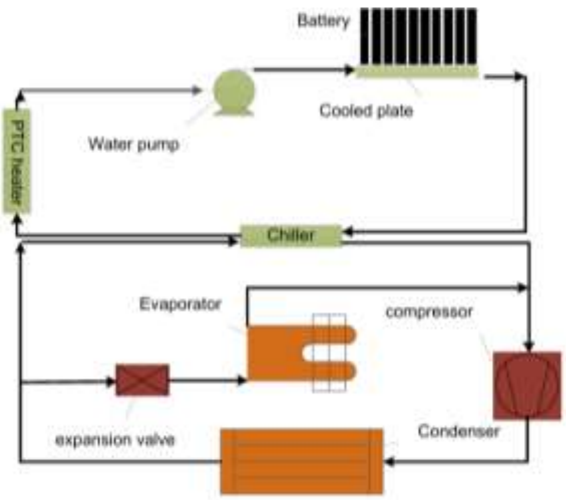


Figure 19. Combined cooling system

Amrutkar and Patil [21] used a 1-D approach to design the car radiator. This can be the optimum use of 1-D analysis as the author was able to obtain the performance curves of the car radiator under different conditions without diving into the details of car radiator design as flow maldistribution and ambient operating conditions. This model can be combined with other 1-D designed components and obtain the required system-level analysis.

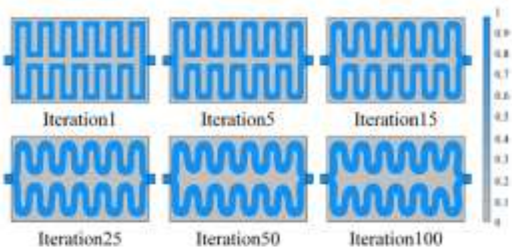
5.2 CFD analysis

CFD is the most widely used approach to create a new design or validate an existing one. Any heat sink design must be validated through CFD modeling in order to ensure the component will behave as intended and to identify weakness areas in the design.

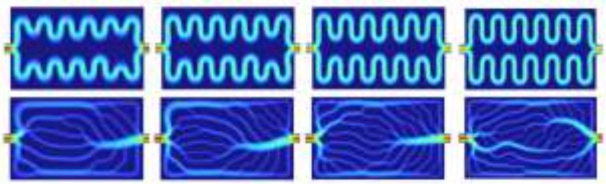
CFD analysis is used not only to validate pre-calculations, but it can also be used to identify the best spots to put the heat-dissipating component to take the best efficiency out of a heat sink [22].

Grace et al. [23] have used CFD modeling in order to optimize the cold plate design by changing channel dimensions and orientations. The model was also used to model the same cold plate but with different coolants to compare the temperature gradients of the components based on the coolant used.

Zhan et al. [8] have used CFD modeling to identify the areas of improvement for the topology-optimized cold plates, as shown in Figure 20.



(a) Cold plate paths optimization

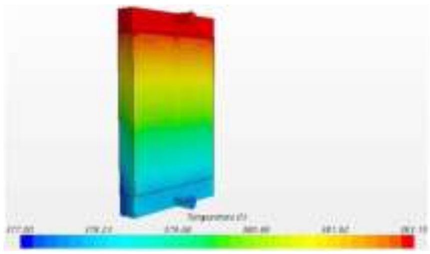


(b) Velocity contours of different cold plate paths

Figure 20. Topology optimization of cold plate paths

Bahuguna et al. [24] have used a technique, CFD analysis, which is the porous media approach, shown in Figure 21, in which the designer does not have to use the accurate CAD file of the heat exchanger, which can have too many details to be modeled with normal computers, as in the case of a car radiator. The car radiator has many details in the fins section, so it will be very costly to accurately perform CFD analysis on it. Instead, the porous media approach is used; its only problem is that it needs some data that only comes from experiments to accurately identify the problem.

(a) Car radiator mesh



(b) Car radiator temperature contour

Figure 21. Porous media approach to the car radiator

Also, Kumar and Gupta [25] have used CFD extensively in order to accurately capture the battery temperature while being cooled with PCM.

Ebere et al. [26] have used CFD analysis to explore the transient behavior of the electronic components under the different types of air-cooling heat sinks.

Bhagat and Deshmukh [27] have used CFD analysis as a powerful way to predict the behavior of the fluid at different times through the cycle. They also came out with the observation that closed-loop evaporative cooling can be the most promising technique in using heat pipes for batteries and electronics cooling.

5.3 Experimental analysis

After designing any component, either by 1-d analysis only or by detailed CFD analysis, experimental analysis must always take place in any system validation procedure.

Gupta et al. [28] have used experimental analysis after performing system-level modeling and also after performing

CFD analysis in order to further ensure the reliability of the system that they have designed. Experimental analysis has shown that the system is not performing as intended at different operating conditions, and this is the importance of experimental analysis.

Trutassanawin et al. [29] have taken a pre-designed refrigeration cooling system and performed experimental analysis on it. The test was made to identify areas for improvement in the cooling system and to determine whether it can be made for mass production or not.

Novikov et al. [14] have directly used PCM in experiments to investigate the behavior of electronic assemblies. The investigation came out with the reliability of the PCM cooling technique, but it could not predict its behavior under different operating conditions, which can be made through different modeling techniques, whether by 1-D analysis or by detailed CFD modeling.

6. CHALLENGES

High power density is the most critical aspect in many applications, specifically in the automotive and aerospace industries. Different cooling techniques are used to achieve the goal, but in the end, the dominant parameter in the industry is how efficient the proposed system is compared to the cost.

Also, it is very important to accurately model the thermal system as it defines how accurate the output will be. As seen from the stated papers, each level of system design has its own problems

In system-level modeling, the problem is how to define the problem and state the assumptions without getting wrong initial results. Also, with CFD modeling, it is very important to account for CAD cleaning, Mesh accuracy, and look for the parameters that most affect the problem during post-processing.

It is worth mentioning that during any design phase, the biggest problem will be the cost, whether it is during simulations, the manufacturing phase, or during operation. This is the key parameter in choosing the effective cooling method, especially for the type of application we are countering.

7. CONCLUSIONS

Based on the papers reviewed, the research needs to be focused on how to increase the power density while maintaining the required junction conditions and keeping the components operating at the required conditions efficiently. Also, the coupling of electrical and mechanical designs from the beginning enhances the final output and helps find the key parameters affecting both cooling and electrical systems to perform at their peak. The cost of the cooling system is the parameter to always look for during any phase of designing a thermal management system.

With the presence of AI during the design phase, it becomes increasingly easier to obtain the optimum cooling system design while maintaining all required operating conditions.

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NOMENCLATURE

EV	electric vehicle
OBC	on-board charger
AC	alternating current
DC	direct current
G2V	grid-to-vehicle
V2G	vehicle-to-grid
V2H	vehicle-to-home
MOSFET	metal–oxide–semiconductor field-effect transistor
SiC	silicon carbide
PCM	phase change material
CFD	computational fluid dynamics
TIM	thermal interface material
RDS	drain-to-source resistance
Rj-c	junction-to-case thermal resistance
Rc-TIM	case-to-thermal interface material resistance
RHS-amb	heat sink-to-ambient thermal resistance
AI	artificial intelligence
PHEV	plug-in hybrid electric vehicle
TEC	thermoelectric cooler
1-D	one-dimensional
CAD	computer-aided design