Proposal for Thermal Management Systems for e-Bike Controllers

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Abstract: The rise in urban e-bike adoption underscores the need for robust thermal management systems to enhance the efficiency and reliability of critical components such as motor controllers. This study explores compact, lightweight, cost-effective cooling systems to maintain optimal thermal conditions under diverse scenarios. A comprehensive review of cooling technologies, including air, liquid, and hybrid systems, highlights the advantages of phase change materials and heat pipe-based solutions, particularly in combination with forced convection. Control systems leveraging fuzzy logic have emerged as the best solution due to their adaptability and low computational requirements. This research establishes a foundation for integrating innovative thermal management architectures into next-generation e-bikes, promoting sustainability and improved user safety.

1 INTRODUCTION

In recent years, society has become increasingly aware of the rise in pollution and the greenhouse effect. This awareness, combined with legislation on emissions and the reduction of energy consumption, has driven the search for more sustainable alternatives (Wu et al., 2017). Until 2020, the transportation sector was the second-largest contributor to greenhouse gas emissions, primarily due to the dominance of fossil fuels, as approximately 91% of the energy consumed in this sector originates from petroleum derivatives (Ritchie et al., 2024; IEA, n.d.). Consequently, the transition to alternative energy sources has become inevitable. This shift has been encouraged by global climate policies, such as the decarbonization targets established at the United Nations Climate Change Conference (COP26), aiming to accelerate the adoption of vehicles that minimize these emissions (United Nations, n.d.).

This transportation shift prioritizes electric vehicles, promoting cleaner, efficient mobility, while e-bikes emerge as practical, sustainable solutions for urban commuting with growing market value and production (Wu et al., 2017; Mordor Intelligence, 2024). The advantages of this mode of transport include flexibility, convenient charging (feasible in any location) and the lack of a licensing requirement, which facilitates its adoption. Moreover, e-bikes offer greater ease of use than conventional bicycles. This makes them particularly suited to densely populated cities, where they contribute to alleviating traffic congestion.

E-bikes are similar to conventional bicycles but feature additional electrical components that provide pedal-assist functionality. These components include an electric motor, typically located in the wheel hub or central region, which assists the rider's movement; a rechargeable battery that supplies energy to the motor; and a controller, which manages the power delivered to the motor based on sensor data, such as cadence and torque sensors, ensuring both efficiency and safety. These elements are, therefore, essential for the proper functioning of this mode of transport, with various types of controllers available, offering different levels of complexity and adaptability to operational conditions.

Advancements in e-bike electronics follow a miniaturization trend, with rising component density, as per Moore's Law (Mollick, 2006). This increase in

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component density results in higher heat generation rates due to the Joule effect, leading to challenges associated with overheating (Băjenescu, 2021). Consequently, there is an imperative need to dissipate this heat to ensure that components operate within their proper temperature ranges and avoid overheating, which could result in performance degradation or equipment damage (Pecht et al., 1992). According to the literature, approximately 55% of failures in electronic equipment are attributed to overheating (Xiahou et al., 2018). Nowadays, while controllers typically feature passive cooling systems, such as fins, these are often insufficient to dissipate all the generated heat. Therefore, it is necessary to develop active cooling systems adapted to existing controllers, ensuring proper operation and preventing damage or performance loss.

For implementation in an e-bike controller, the developed solution must meet essential requirements, including compactness, low weight, resistance to impacts and vibrations, low energy consumption, cost-effectiveness, and ease of maintenance, as well as protection against contaminants such as water and dust. A market analysis of controllers revealed that these components typically achieve efficiencies of around 90% (Kelly Controls Inc, 2024), with the power output of the most common e-bike motors ranging from 250 to 1000 W (Li, 2023), resulting in a maximum heat output of around 100 W. Furthermore, the typical dimensions of these components range from $100\,mm \times 60\,mm \times 30\,mm$ to $200\,mm \times 100\,mm \times 50\,mm$.

As e-bikes continue to gain popularity, the reliability of their components becomes increasingly critical. Implementing cooling systems will extend the lifespan of controllers and reduce costs associated with maintenance and replacement, thereby promoting broader and more sustainable adoption. Additionally, temperature regulation of electrical components prevents failures, safeguarding user safety. Moreover, improving the efficiency of control systems will result in more efficient energy consumption (Ali et al., 2024), aligning with environmental goals of reducing emissions and energy usage.

2 LITERATURE REVIEW

E-bike controllers, like other electronic components, are subjected to varying operating conditions, including fluctuations in temperature and load, primarily due to prolonged periods of continuous use. Such conditions can lead to equipment overheating, compromising performance, and lifespan reduction, with critical failures potentially occurring in extreme cases (Băjenescu, 2021). The literature has explored and proposed various cooling systems aimed at improving the efficiency of electrical systems, ensuring they adequately meet the thermal requirements demanded during operation (Ali et al., 2024; Lu et al., 2019; Y. Wu et al., 2024).

Despite the increasing use of e-bikes, the literature does not provide significant information on cooling systems for controllers, with the sole exception of You-Ma Bang et al. (Bang et al., 2016). The available literature focuses exclusively on cooling solutions for battery modules in electric vehicles and electronic components such as Central Processing Units (CPUs). Therefore, this section will describe the most used technologies for dissipating heat in electronic systems, to provide a comprehensive overview of existing systems. Subsequently, specific solutions reported in the literature will be examined in detail, highlighting the advantages and disadvantages of each approach. Finally, literature addressing thermal control algorithms will be analyzed, enabling the adaptation of solutions to operational conditions.

2.1 Existing Technologies

According to the literature (Y. Wu et al., 2024; Lu et al., 2019), cooling systems can be categorized into three groups based on the need for external energy consumption. Active systems require the input of external energy to create artificial conditions that are difficult to achieve naturally (Y. Wu et al., 2024). Conversely, if the solution does not require external energy and relies solely on environmental conditions to operate, it is considered a passive technology. In passive systems, the cooling medium moves through forces such as capillary action or gravity, among others, to transfer heat away from the system. Finally, if the solution combines active and/or passive technologies, it is classified as a hybrid system. As shown in Figure 1, the primary passive systems include phase change materials (PCM), heat pipes (HPs), and fin-based systems, whereas the most common active systems utilize air cooling, liquid cooling, and thermoelectric cooling (TEC) modules.

2.1.1 Air Cooling

Air cooling systems, widely used in electronics, rely on natural or forced convection for simple and cost-effective heat management (Y. Wu et al., 2024). Adding a fan increases air velocity and improves heat removal efficiency. These systems benefit from their

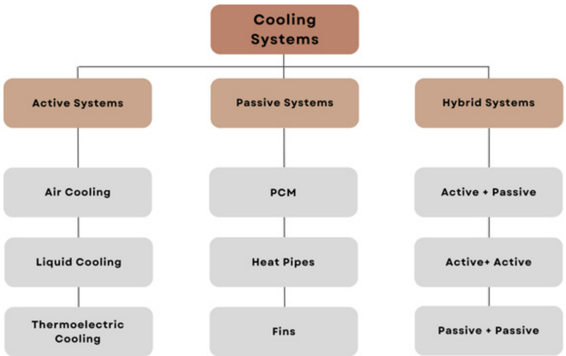

Figure 1: Classification of refrigeration systems, adapted from (Y. Wu et al., 2024).

simplicity, compact size, lightweight design, low cost, and elimination of electrical short-circuit risks due to leaks (Y. Wu et al., 2024). Their effectiveness depends on airflow velocity, surface geometry, and airflow-surface interactions (Bergman et al., 2018), with additional components like deflectors often used to direct airflow.

2.1.2 Liquid Cooling

Liquid cooling uses a closed circuit where coolant absorbs and dissipates heat, driven by a pump. Key components include a heat exchanger (or radiator) for heat dissipation and a reservoir for fluid storage. Cooling is achieved either through direct contact—where components are submerged in the fluid, enhancing temperature uniformity but posing risks like short circuits—or indirect contact, where heat is transferred via heat sinks or cold plates to the coolant flow (Y. Wu et al., 2024). These systems are extensively used in industrial production, electronics, and Battery Thermal Management Systems (BTMS) due to their superior heat removal efficiency (Y. Wu et al., 2024).

Their primary advantages lie in their high heat removal capacity, attributed to the superior thermal conductivity of liquids compared to air, enabling greater reductions in the maximum temperatures of electronic components (Y. Wu et al., 2024). On the other hand, the main disadvantages of liquid cooling systems are related to their complexity, which results in significant space requirements, as well as the potential for leaks. These leaks must be carefully mitigated using high-quality seals, which increase the solution's overall cost (Lu et al., 2019; Y. Wu et al., 2024).

2.1.3 Heat Pipes-Based Cooling

HPs are devices capable of efficiently transferring heat with minimal temperature drops, operating based on the phase change of the working fluid. These systems exhibit very high effective thermal conductivities, surpassing those of many known metals (Y. Wu et al., 2024), which is advantageous for heat exchange applications.
Traditional HPs comprise three fundamental components: the enclosure, the working fluid, and the wick structure. The enclosure isolates the working fluid from the environment, ensuring leak prevention and effective thermal conductivity. The working fluid facilitates heat transfer, requiring properties such as high thermal conductivity, high latent heat of vaporization, low viscosity, and high surface tension (Y. Wu et al., 2024). The wick structure generates capillary pressure to drive fluid movement within the system. These systems are further divided into three main sections: the evaporator, the adiabatic section, and the condenser. Heat is introduced at the evaporator, transferring energy to the working fluid, causing it to evaporate and increasing the local pressure, which drives the fluid toward the condenser. In the condenser, the latent heat is released, causing the fluid to return to its liquid state. Finally, capillary pressure and surface tension guide the fluid back to the evaporator, restarting the cycle (Murshed et al., 2017). This technology can operate in any orientation, maintaining capillary pressure sufficient to overcome gravity when the condenser is positioned below the evaporator.

There are various configurations of Heat Pipes, with the most common being Flat Heat Pipes (FHPs) and Pulsating Heat Pipes (PHPs, also referred to as Oscillating Heat Pipes - OHPs) (Y. Wu et al., 2024; Lu et al., 2019). The operating principle of these types of HPs is the same as that of conventional HPs, with the primary difference being the geometry of the solution. FHPs feature a flat surface in the evaporator region to enhance contact with flat components, while PHPs consist of a tube bent multiple times into a serpentine shape. Unlike conventional HPs, PHPs lack a capillary structure, and the fluid motion is driven by pressure pulsations between the evaporator and condenser regions.

2.1.4 PCM-Based Cooling

PCMs are increasingly utilized in Thermal Management Systems (TMS) due to their high energy storage capacity, driven by their substantial latent heat (Murshed et al., 2017). The optimal performance is achieved when PCMs operate at their phase change temperature, maximizing heat absorption (Y. Wu et al., 2024; Murshed et al., 2017). Additionally, they are primarily classified based on their phase change type, with solid-solid and solid-liquid PCMs being the most common due to their stability and integration ease (Y. Wu et al., 2024). PCMs can also be categorized as organic or inorganic. Organic PCMs, such as paraffin, offer high latent heat, good stability, and no subcooling requirements (the need to cool below the phase change temperature to solidify) but have lower thermal conductivity and reduced stability. In contrast, inorganic PCMs exhibit superior latent heat and thermal conductivity but are less reversible and prone to subcooling (Y. Wu et al., 2024). The ideal PCM should combine high latent heat, excellent thermal conductivity, and durability over multiple phase change cycles.

These materials are notable for their high energy storage capacity, zero energy consumption, low cost, and compact size. They also mitigate temperature peaks and promote thermal uniformity (Lu et al., 2019). However, their main drawbacks are related to subcooling phenomena, low thermal conductivity, and limitations in cyclic operations. In cyclic applications, the stored heat must be dissipated before the next cycle begins, ensuring that the PCM can absorb heat again. This prevents PCM from fully changing phases and losing its properties. Therefore, for cyclic operations or prolonged usage, an auxiliary system, such as air cooling, is required to preserve the PCM's characteristics (Ling et al., 2015).

2.1.5 Thermoelectric Cooling

Thermoelectric modules utilize two different types of semiconductors to convert thermal energy into electrical energy (Seebeck effect) or electrical energy into a temperature difference (Peltier effect), enabling their use as coolers (TEC) or heat generators (TEG) (Lu et al., 2019). Due to the application of electrical current, a temperature difference is created between the two sides of the module, resulting in one side being colder (cold side) and the other side being hotter (hot side). The main advantages of these components include a lack of moving parts, no refrigerants, and compactness (Murshed et al., 2017), but they suffer from low energy conversion efficiency, high material costs, and require cooling for the hot side (Y. Wu et al., 2024; Lu et al., 2019). Despite being in early research stages, particularly for BTMS, thermoelectric modules show cooling potential comparable to liquid systems (Y. Wu et al., 2024).

2.1.6 Hybrid Cooling

After presenting all the cooling technologies, it is evident that each has its advantages and disadvantages. Additionally, it can be concluded that no single solution, on its own, is fully effective in addressing the problem of excessive heat. Consequently, to propose a more robust solution, these technologies are often combined, leveraging the advantages of some to mitigate the limitations of others (Ali et al., 2024). The literature provides several examples of solutions that integrate different technologies, some of which are described in the following sections.

Ziye Ling et al. (Ling et al., 2015) proposed a hybrid battery cooling system combining PCM (RT44HC with Expanded Graphite - EG) and forced convection to address PCM limitations under extreme conditions, such as complete melting and loss of latent heat. Comparing forced and natural convection, the study showed that passive systems performed adequately under low loads but failed at higher loads, where insufficient heat dissipation led to PCM melting and rising battery temperatures. In contrast, the hybrid system efficiently cooled the PCM, maintaining temperatures below 46°C (its phase change temperature) between cycles, enabling full recovery of latent heat capacity and consistent performance. Additionally, the system's temperature uniformity was satisfactory for both the passive and hybrid solutions, with a maximum temperature difference of less than 3°C. This uniformity is attributed to the high thermal conductivity of the PCM used, which was possible by the addition of EG. In summary, this study demonstrates the distinct roles played by PCM and forced convection within the system. The PCM is responsible for controlling the maximum temperature and ensuring temperature uniformity, while forced convection enables the PCM to recover its energy storage capacity between cycles, preventing the degradation of its properties.

Although the described study successfully combined PCM with forced convection, it does not explore potentially more efficient or cost-effective alternatives, such as the use of different types of PCMs or optimizations in airflow design. Incorporating longer or more variable testing, including structural design modifications, could provide additional insights into the practical feasibility and efficiency of the solution. Finally, this system offers a simple structure with high efficiency and reliability, making it a suitable candidate for application in an e-bike controller.

On the other hand, J. Stafford et al. (Stafford et al., 2012) developed a solution exploring the possibility of replacing a large fan with an array of smaller fans, offering greater flexibility. They tested two distinct configurations: one with two axial fans and another with three fans, each with a diameter of 24.6 millimeters, arranged in a line. These fans provide cooling through the impact of air on finned heat sinks. Additionally, two different scenarios were tested: one where the air could exit the heat sink in all directions ("4-exit") and another where one direction was blocked ("2-exit"), simulating a scenario where thermally sensitive components are present in that direction. The results showed improved heat transfer with the "4-exit" setup due to air recirculation, while "2-exit" reduced performance due to crossflow effects. The three-fan array outperformed the large fan by 35% at 9,000 rpm (central fan) and 21% at 7,000 rpm (peripheral fans), though performance dropped at higher speeds. The two-fan array matched a single fan up to 10,000 rpm but underperformed beyond that.

Based on this study, it can be concluded that the use of multiple fans can offer advantages in terms of design flexibility, temperature uniformity, and efficiency for applications with limited space. Therefore, due to the spatial constraints in e-bikes, the implementation of smaller fans, rather than a single larger one, could be a viable solution to enhance performance without increasing the occupied volume.

Paisarn Naphon et al. (Naphon et al., 2012) proposed a cooling system for a CPU based on a Vapor Chamber. This system operates similarly to Flat Heat Pipes and is composed of two copper plates (upper and lower), a wick structure that facilitates the flow of the liquid phase (condensate) back to the evaporator region (located on the lower plate) through capillary action, and sinter columns, which ensure proper fluid distribution within the chamber and provide internal structural support. These components ensure efficient fluid circulation, preventing dry-out (where fluid circulation ceases, resulting in the absence of fluid in the evaporator and a consequent temperature increase within the chamber) and enabling effective heat transfer, hotspot mitigation, and temperature uniformity. Additionally, a heat sink was attached to the condenser region, increasing the heat removal surface area and enhancing heat dissipation. An axial fan was also added to further improve energy dissipation, as illustrated in Figure 2. Compared to a conventional copper plate system, the Vapor Chamber achieved 6.89% lower CPU temperatures and 10.53% lower energy consumption for 90% of CPU's maximum load, leveraging latent heat for superior performance. Optimal results were achieved with smaller heat input areas and sufficient fluid levels, ensuring stronger capillary action and efficient heat distribution.

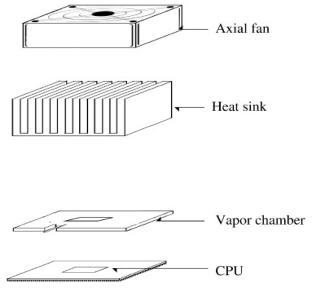

Figure 2: Diagram of the solution (Naphon et al., 2012).

This solution can be employed for cooling the controller of an e-bike due to its structural simplicity, compact dimensions (60 mm × 60 mm × 3.8 mm), absence of moving parts, and thermal efficiency. However, the study could have explored alternative working fluids to determine which properties yield the most optimal performance.

Xinxi Li et al. (X. Li et al., 2019) proposed a cooling system for a lithium battery module utilizing a thermoelectric cell, with its hot side attached to a heat sink. Additionally, an axial fan was incorporated to induce forced convection and enhance heat dissipation from the heat sink. The results demonstrated that the proposed system outperformed both natural and forced convection systems (using only the fan and heat sink without the thermoelectric module), achieving lower battery cell temperatures and reduced rates of temperature increase. For a battery discharge rate of 3C, the proposed solution achieved a maximum temperature of 65.43 °C, compared to 70.525 °C for the system without the thermoelectric module (using only a heat sink and forced convection) and 78.30 °C with natural convection alone. Additionally, the proposed solution demonstrated improved temperature uniformity.

The tests conducted demonstrate that thermoelectric modules are effective in reducing the temperature of electrical components. However, they should only be employed in extreme situations, serving as an additional safety measure rather than operating continuously. Continuous operation would result in high energy consumption due to the low efficiency of these devices.

Qingchao Wang et al. (Wang et al., 2015) proposed a solution for a BTMS consisting of PCM and an OHP, with paraffin chosen as the PCM due to its low cost, good thermal storage capacity, and melting point (≈ 41°C). In the presented solution, the evaporator of the OHP is located within the PCM, which is positioned in the space between the battery cells to remove heat from them. Therefore, the PCM delays battery overheating by absorbing heat during phase change, while the OHP, using acetone as the working fluid (boiling point of approximately 56°C), transfers heat from the PCM to a water-cooled condenser. Results showed temperature delay improvements of 68.36%, 81.33%, 57.92%, and 37.01% at power levels of 20, 25, 30, and 35 W, respectively. However, as the power increases, this effect diminishes because PCM's energy storage capacity is depleted. This situation could be mitigated if the PCM had a higher thermal conductivity, or if the OHP started operating at a lower temperature than the PCM's phase change temperature, thereby efficiently removing heat from it. This does not occur because the OHP’s operating temperature coincides with the boiling temperature of its working fluid, which is higher than the PCM’s phase change temperature.

In conclusion, compared to solutions with natural convection, the proposed solution exhibits lower maximum temperatures, which is the intended outcome. However, it is not feasible to implement it in an electric bike controller due to the need for a vacuum pump, which is essential to ensure the proper operation of the OHP. On the other hand, from the work presented, it can be concluded that this system was not well designed. Therefore, when used with PCM, the HPs should have internal fluids with boiling temperatures lower than the phase change temperature of the PCM, ensuring that the PCM does not completely undergo a phase change.

Wayan Nata Septiadi et al. (Septiadi et al., 2022) proposed a BTMS for e-bike using PCM, traditional Heat Pipes and forced ventilation. To enhance PCM conductivity and stability, 20% in mass of expanded graphite was added to paraffin, increasing liquid phase stability (as the liquid fraction was retained in the EG pores due to capillary forces) and thermal conductivity by 107 times but reducing latent heat and storage capacity. As shown in Figure 3, the PCM surrounds the batteries, absorbing their heat and transferring it to the evaporator, with fins on the condenser improving heat dissipation. Tests showed temperature reductions of 1.84°C, 2.69°C, and 6.62°C compared to a battery without a cooling system, for discharge rates of 0.5, 1, and 1.5C, respectively, with excellent temperature uniformity. Forced convection further reduced cell temperatures and improved uniformity as fan speed increased.

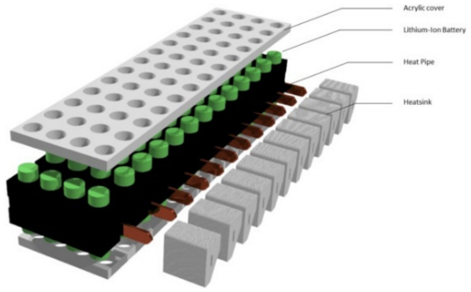

Figure 3: Exploded view of BTMS (Septiadi et al., 2022).

From the analysis of the work described, it can be concluded that the presented system is effective in dissipating heat from a battery and could also be adapted for use in an e-bike controller due to its compact design. Once again, it was confirmed that PCM is a viable solution for lowering battery temperatures while promoting good thermal uniformity. However, the battery temperature consistently remained below the phase change temperature of the PCM composite (≈41.6°C), suggesting that the PCM may not have undergone a phase change and instead functioned as a thermal conductor rather than an energy storage medium. This hypothesis is supported by the observation that increased ventilation led to a reduction in battery temperature—an outcome unlikely if the PCM were partially melted, as this process is nearly isothermal. Consequently, if this scenario is accurate, it implies that for the tested discharge rates, the number of heat sinks or the fan speed could be reduced. This would lower costs and energy consumption while ensuring PCM undergoes a phase change, fully utilizing its properties.

Finally, Y. Salami Ranjbaran et al. (Ranjbaran et al., 2023) proposed a hybrid battery cooling system combining PCM and air cooling to enhance efficiency with minimal energy use. The design includes PCM-filled containers between battery cells and air channels for cooling. Simulations tested nine scenarios by varying passageways (number of vertical sections from 2–4) and air pressure (1.1–1.3 atm) to evaluate key parameters. Results showed that more passageways or higher inlet pressure reduced battery temperature, which remained below 314K (≈41°C) in all tests. Additionally, the results revealed that PCM's performance depends on its melted fraction. If this fraction is very low, heat conduction is promoted, which is not the most effective heat transfer mode for PCM due to its low thermal conductivity. The optimal PCM performance occurred with a melted fraction of 15–25% to 60–70%, as excessive melting caused insulation effects.

Temperature differences within the battery were minimal, with a maximum of 1.57°C for four passageways.

In conclusion, this solution demonstrates high versatility, making it easily adaptable for electric bike controllers. Furthermore, it can be tailored for systems with higher thermal demands by utilizing PCMs with greater thermal conductivities, thereby facilitating faster heat transfer to dissipation sites. Increasing ventilation power or the quantity of PCM could also be viable strategies, although these may introduce challenges related to higher energy consumption and increased system weight. Additionally, to enhance heat dissipation, fins can be incorporated either within the cooling channel or on other air-exposed surfaces, thereby increasing fluid contact area and improving heat dissipation efficiency. In summary, this solution shows significant potential for electric bike controllers due to its flexibility.

Additionally, cooling solutions for components of e-bikes and electric scooters, such as battery modules, have been explored in the literature. Chandra Sahwala et al. (Sahwal et al., 2022) developed an algorithm to control the temperature of various elements in the powertrain of e-bikes and electric scooters using two coolant loops and a refrigeration loop. However, this system is highly complex and spatially demanding, as it includes pumps for fluid circulation, compressors, radiators, and condensers, in addition to pipes for coolant flow. Therefore, such configurations are excessively intricate and impractical for traditional e-bikes and electric scooters due to spatial constraints. Similarly, Jaydeep M. Bhatt et al. (Bhatt et al., 2021) developed a BTMS based on evaporative cooling to assess its impact during the charging process of lead-acid batteries in e-bikes and electric scooters. This approach has proven to be highly effective in reducing battery temperature and ensuring a uniform thermal distribution among the cells throughout charging. However, as in the previous case, the system exhibits high complexity and requires considerable space due to the need for additional components, such as an air blower and liquid reservoirs. Consequently, such solutions are unfeasible for conventional e-bikes and electric scooters due to space limitations and can only be used as a plug-in to enhance the charging process.

On the other hand, You-Ma Bang et al. (Bang et al., 2016) optimized the geometry of a heatsink and demonstrated the inability of passive systems to effectively control the temperature of controllers. Thus, it is crucial to find a balance between spatial constraints and thermal efficiency, as proposed by Wayan Nata Septiadi et al. (Septiadi et al., 2022).

2.2 Control Systems

An active system should also include a monitoring and control system to ensure that the cooling adapts to operating conditions. In this way, the active system can increase or decrease its cooling capacity by adjusting parameters such as fan speed, which helps reduce energy consumption compared to continuous operation scenarios.

2.2.1 Existing Control Systems

The literature identifies various algorithms for controlling the system and ensuring appropriate operating conditions (Ali et al., 2024). PID (Proportional-Integral-Derivative) controllers are popular for their simplicity and effectiveness but rely on predefined parameters, limiting optimal performance (Ali et al., 2024). On the other hand, Fuzzy Logic Controllers (FLC) use linguistic variables and "If-Then" rules, based on the designer's experience and intuition, to handle nonlinear systems and uncertainties, excelling in scenarios lacking precise mathematical models (Ali et al., 2024). Advanced approaches include AI-based algorithms like Deep Learning (DL) and Artificial Neural Networks (ANN), which improve efficiency and overall performance but require extensive training data (Ali et al., 2024). Model Predictive Control (MPC) dynamically adapts to real-time data, offering superior performance under dynamic conditions, being a forward-looking methodology, i.e. oriented towards the future (Ali et al., 2024). Finally, there are hybrid systems that combine multiple control algorithms to increase the efficiency, robustness, and adaptability of controllers.

2.2.2 Developed Controllers

Shupeng Zhang et al. (Zhang et al., 2023) developed a battery heating system using an electrothermal film powered by the battery and regulated by a FLC. This controller was chosen for its simplicity, low computational requirements and the lack of a requirement for prior data compared to Dynamic Programming (DP), which, although optimal, is unsuitable for real-time systems. Since the energy used for heating is drawn from the battery, it is crucial to establish a balance between energy consumption and heating to optimize the vehicle's range. The block diagram of the proposed controller is presented in Figure 4, showing that the controller incorporates three inputs: State of Energy (SoE), battery temperature, and motor load to adjust heating power dynamically. To evaluate the proposed solution under dynamic driving cycles, tests were conducted comparing the proposed FLC-based solution, a continuous heating system operating at maximum power, a system without heating, and one using DP for different initial battery temperatures and SoE levels. The results revealed that the FLC achieved a range improvement of 3.6 to 5.3% compared to the continuous maximum-power heating system and 5.8 to 150.4% compared to the system without heating. Furthermore, the FLC exhibited a range performance very close to that achieved with DP, demonstrating that FLCs can deliver near-optimal solutions while requiring significantly lower computational power.

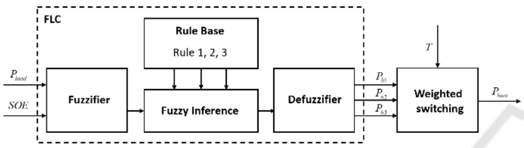

Figure 4: Block diagram of used FLC (Zhang et al., 2023).

Yanqi Diao et al. (Diao et al., 2024) designed a hybrid Fuzzy Logic-PID controller for hypersonic vehicle nose cooling systems, addressing PID limitations in adaptability to varying conditions, due to predefined parameters. Therefore, the FLC dynamically adjusts PID terms, enabling scenario-specific adaptation. Compared to a standalone PID baseline, the hybrid controller achieved similar performance under static conditions but outperformed in dynamic scenarios, with faster stabilization and reduced temperature oscillations. This highlights the hybrid controller's robustness and improved performance through adaptive PID parameter tuning, showcasing the advantages of combining control methods for complex systems.

M. A. Hannan et al. (Hannan et al., 2019) developed an enhanced FLC with a population-based optimization technique, particularly Particle Swarm Optimization (PSO), to regulate lithium battery temperatures, addressing performance degradation outside the optimal range. PSO was used to optimize FLC membership functions, which define how inputs and outputs are converted between real values and fuzzy variables, as can be seen in Figure 5. The proposed algorithm outperformed both FLC and PID controllers in simulations, achieving better stabilization times (PID: 88 min, FLC: 40 min, PSO-FLC: 32 min) and lower overshoot. Additionally, it was observed that the proposed algorithm presented similar results to the FLC, albeit superior, indicating that the optimization algorithm contributed to improved performance over the conventional controller. Therefore, it is possible to conclude that the precise definition of membership functions is critical. However, the results obtained were limited to simulations and were not experimentally validated. Additionally, the author could have considered other metrics, such as the execution time of the algorithms. Lastly, due to its iterative nature, PSO requires a model or prior data to evaluate the various potential solutions within the domain and identify the optimal one. Therefore, in the absence of such data or models, the application of PSO becomes unfeasible.

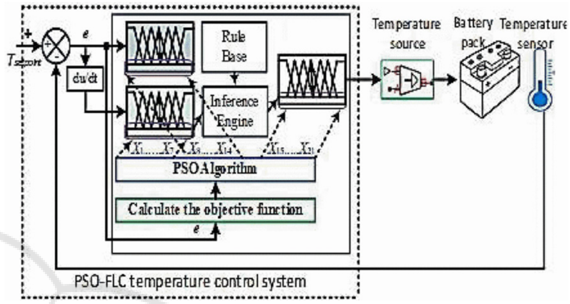

Figure 5: Proposed PSO based FLC algorithm implementation (Hannan et al., 2019).

3 CRITICAL ANALYSIS

The proposed solution, as outlined in Section 1, prioritizes compactness and lightweight design, excluding liquid-based cooling systems due to their space demands and high maintenance. Air cooling systems stand out for their simplicity, low cost, space efficiency, and versatility. They can be combined with other systems, such as PCM, to enhance temperature uniformity. Replacing a larger fan with several smaller ones can increase design efficiency and flexibility, while also promoting better temperature uniformity. All these characteristics make air cooling systems suitable for this application. On the other hand, PCMs are promising due to their ability to absorb large amounts of heat, regulating the temperature of the controller to the phase-change temperature. Therefore, it is crucial to select a PCM with a phase-change temperature below the maximum allowable limit of the component. However, these materials need to be housed in enclosures to prevent leakage of the liquid phase and potential short circuits, complicating their cooling. Thus, despite the high potential of PCM, precautions must be taken to ensure it remains within the optimal liquid fraction range, enhancing the system's performance and preventing a complete phase change, which could lead to a failure of the cooling system. Similarly, HPs can also be suitable for the solution. Traditional ones, due to their circular shape, can be used in conjunction with other technologies, such as PCM, to improve heat removal efficiency. However, on their own, they have low efficiency due to the small contact area. The use of OHPs is not viable for this application due to the need for a vacuum pump, which is too large for this use. Finally, Flat HPs can be used on flat surfaces due to their geometry. These systems are effective in conducting heat from the hot surface to the area where the heat will be dissipated, with a lower thermal resistance than that of a copper plate. Thermoelectric modules enable rapid and controlled cooling, being ideal for high heat dissipation requirements. However, the efficiency of these devices is limited and decreases as the temperature difference between the hot and cold sides increases, which makes these systems less effective for prolonged use. Therefore, the use of thermoelectric modules may be more suitable as a backup solution, complementing other cooling systems, particularly in extreme heat situations when other technologies are unable to remove the required amount of heat. Finally, fins can be used in any solution, increasing the contact area with the heat dissipation medium without increasing the volume of the system, leading to higher energy dissipation.

Based on the analysis of the literature, PCM emerges as an ideal solution, ensuring thermal uniformity and peak absorption. In turn, the cooling of this material can be carried out through channels, as proposed by Ranjbaran (Ranjbaran et al., 2023), with thermoelectric modules also available to assist cooling in extreme scenarios. This solution can be enhanced by optimizing the channel flow, through channel geometry, or by adding fins, enabling higher heat dissipation. On the other hand, cooling could be achieved using traditional HPs, with the evaporator placed inside the PCM. In this case, the heat absorbed by the PCM would be conducted through the HP and dissipated in the condenser. Both scenarios would use fans to promote forced convection, ensuring greater heat removal capacity. Thus, both described solutions are compact and can be controlled to reduce energy consumption, and increase battery autonomy.

Based on preliminary calculations and considering that the e-bike controller generates 100W of heat and the battery can only operate continuously under these conditions for 2 hours, approximately 720 kJ of thermal energy are generated (Eq. 1). To store this amount of energy and considering a PCM with a latent heat of fusion (C) of 195 $\mathrm{kJ/kg}$ (pure paraffin (Wang et al., 2015)), approximately 3.7 kg of paraffin is required (Eq. 2), equivalent to a volume of $4.5\times10^{-3}\ \mathrm{m}^3$, assuming a liquid density of 910 $\mathrm{kg/m}^3$ (Wang et al., 2015). However, as noted, the molten fraction of the PCM must remain below 70% to ensure proper operation. Taking this limitation into account, the required amount of paraffin increases to 5.27 kg (Eq. 3), representing a volume of $5.97\times10^{-3}\ \mathrm{m}^3$ (PCM's density $= 0.7\times910+0.3\times822 = 883.6\ \mathrm{kg/m}^3$). This value represents the maximum quantity of PCM needed in the absence of an active cooling system. As discussed, a cooling system will be incorporated, which will allow for a reduction in the required PCM volume.

$$E = P\times t = 100\ \mathrm{W}\times 2\times 3600 = 720\ \mathrm{kJ} \quad (1)$$

$$720 = m\times C \Leftrightarrow m = 720/195 = 3.7\ \mathrm{kg} \quad (2)$$

$$m = \frac{720/195}{0.7} = 5.27\ \mathrm{kg} \quad (3)$$

The control system to be adopted must have a processing demand that is not excessively high, so it can be applied in real-time on microcontrollers such as an ESP32 microcontroller, which have limited computational and energy resources. Additionally, as this project is in an early phase without detailed thermal data or models, control system selection must reflect these limitations. Iterative, AI-based, or predictive algorithms are excluded, making PID controllers and FLC promising options. However, it would still be difficult to select the ideal PID parameters to maximize controller performance. Therefore, in the early stage, the FLC seems to be the best solution, due to its ease of implementation, computational efficiency, simplicity, and the fact that it is based on experience and intuition. Developing precise rules and membership functions will be key to optimizing performance, requiring empirical testing and validation to ensure adaptability to varying conditions without overloading computational resources.

After the solution is developed and the control system is implemented, the tests conducted will enable data collection that can serve as a foundation for the development of more complex models. This data could be used to refine the FLC rules, explore hybrid controllers such as FLC-PID, or even implement artificial intelligence to develop more advanced predictive models. While these algorithms may increase computational demands, this can potentially be mitigated by using remote servers to perform the necessary calculations.

4 CONCLUSIONS

By evaluating various cooling technologies, PCMs and heat pipe-based systems stand out for thermal efficiency, compactness, and temperature peak management. The combination of PCMs with auxiliary cooling methods, such as forced convection, further enhances system performance while maintaining compactness and energy efficiency. In the literature review, there was found a lack of information regarding active cooling solutions for controllers. Thus, the development of this novel solution will enrich the literature and foster advancements in this field, particularly in the design of compact systems suitable for space-constrained applications, providing a viable alternative to liquid-based cooling solutions, which are impractical in such scenarios.

Control strategies, particularly those leveraging fuzzy logic, were highlighted for their adaptability and low computational overhead, making them suitable for real-time application on resource-constrained microcontrollers. These approaches also lay the groundwork for future optimization through advanced algorithms and data-driven models.

By adopting the proposed hybrid cooling system combining phase change materials with auxiliary methods such as forced convection, e-bike controllers can achieve improved thermal management, significantly extending their operational lifespan and reliability. Implementing fuzzy logic-based control strategies ensures that these systems are energy-efficient and adaptable to dynamic operating conditions, further enhancing battery life and safety. This integration not only aligns with global environmental and sustainability goals by reducing energy waste and promoting e-bike adoption but also supports the development of resilient urban mobility solutions. Consequently, these advancements can catalyze the shift towards greener, more efficient transportation networks, delivering tangible benefits to users, and society.

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