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THE EFFECTS OF APPLYING AIR COOLING WITH COPPER TUBE SYSTEM ON THE THERMAL MANAGEMENT OF CONCAVE BATTERY PACKS

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ABSTRACT

Electric vehicles are rapidly becoming a key component of sustainable transportation technologies. One of the critical factors directly affecting their performance and safety is the effective thermal management of battery packs. Inadequate thermal control can lead to reduced battery lifespan and increased safety risks. In this context, the present study comprehensively investigates the thermal performance of copper pipe-assisted air cooling systems integrated into battery packs with concave cell arrangement geometry. Both numerical and experimental methods were employed to analyze the effects of varying pipe numbers and air velocities on the battery temperature distribution. The results demonstrated that multi-pipe systems provide more uniform temperature distribution and enhanced cooling efficiency compared to single-pipe configurations. Particularly, the two-pipe system emerges as a balanced and practical solution in terms of both performance and system complexity. This study offers valuable insights for the design of optimized thermal management systems ensuring the safe and efficient operation of electric vehicle battery packs. Furthermore, the developed numerical modeling approach is adaptable to various battery geometries and operating conditions, contributing to accelerated and reliable design processes.

1. INTRODUCTION

Energy is considered one of the most strategic inputs in achieving the sustainable development goals of modern societies. In today's world—where industrialization is accelerating, urbanization is expanding rapidly, and technological infrastructure is advancing—global energy demand continues to increase steadily. This growing demand necessitates new solutions not only in terms of energy quantity but also regarding the renewability of sources, environmental impacts, and economic sustainability [1-2]. Fossil fuels, which have served as the driving force of economic growth for centuries, are now being deprioritized in energy policies due to their finite reserves and their role in exacerbating climate change through carbon emissions. To reduce the carbon footprint of energy production and minimize its environmental burden, many countries have initiated transitions toward more sustainable energy systems. In this context, renewable energy sources such as solar, wind, hydroelectric, biomass, and geothermal have come to the forefront as alternative solutions for energy generation [3-4]. One of the sectors where the impact of this energy transition is most strongly felt is transportation. Road transportation accounts for a significant portion of global energy consumption and greenhouse gas emissions. Conventional vehicles powered by internal combustion engines are misaligned with sustainable transportation goals due to their high fuel consumption, low energy conversion efficiency, and contribution to air pollution. Consequently, in recent years, there has been a marked shift from fossil fuel-powered vehicles to electric vehicles (EVs) [5-6].

EVs are considered environmentally friendly transportation solutions due to their advantages such as lower carbon emissions, reduced energy loss, and high efficiency. However, the success of these systems largely depends on energy storage technologies, particularly battery performance [7-8]. Today, LiB are

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the most widely used energy storage units in EVs, favored for their high energy density, long cycle life, low self-discharge rate, and lightweight design. Although LiB can operate within a temperature range of -40 °C to 50 °C, optimal performance and longevity require maintaining their temperature between 20 °C and 40 °C. Moreover, keeping the temperature difference between battery cells below 5 °C is critical for both system efficiency and safety. Failure to maintain these conditions can lead to capacity loss, reduced cycle life, decreased efficiency, and significant safety risks. Uncontrolled temperature rises, in particular, may cause thermal runaway, which can result in the release of hazardous gases, smoke, fire, and even explosions [9-10]. To mitigate these risks and ensure the safe, efficient, and stable operation of batteries, Battery Thermal Management Systems (BTMS) have been developed. BTMS integrates heating, cooling, and insulation technologies to keep battery temperatures within the desired range and minimize temperature differences between cells. Generally, BTMS can be categorized into passive and active systems. Passive methods, such as natural convection, phase change materials (PCM), and heat pipes, offer low-energy, structurally simple solutions but exhibit limited performance in high energy density applications. Active BTMS, on the other hand, use external energy sources to achieve more effective temperature control. The most common active cooling methods are air and liquid cooling. Air-cooled systems are preferred for their low cost, simple design, and easy integration; however, due to low thermal conductivity, they often fail to provide adequate thermal performance in high-power battery applications. In contrast, liquid cooling systems offer a more effective solution by enabling faster and more uniform heat dissipation thanks to their superior thermal conductivity. Factors such as the type of coolant (e.g., water, ethylene glycol, mineral oils, nanofluids), flow direction, battery cell arrangement, and piping structure directly influence system performance [11-16].

Thermal management of LiB is critical for battery safety, performance, and cycle life. In this context, the literature contains numerous studies examining the performance of air-cooled and copper pipe-assisted cooling systems under different configurations.

Zhang et al. [17] investigated the thermal performance of air-cooled battery systems with different air outlet positions and demonstrated that increasing the air velocity and appropriately positioning the outlet significantly improved thermal equilibrium in the battery pack.

Singh et al. [18] analyzed forced convection air cooling using an electrochemical–thermal coupled model and reported that increasing the air velocity improved heat removal from the battery surface. However, the fact that the temperature difference remained nearly constant as the number of cells increased revealed that increasing the air velocity alone is insufficient to achieve a homogeneous temperature distribution in large-scale battery modules. This situation demonstrates that thermal imbalance between cells is a structural limitation in systems where air cooling is used alone.

Alihosseini and Shafaee [19] proposed a copper heat pipe cooling system for a package consisting of 18 prismatic batteries. The heat pipes, integrated through aluminum plates placed between the batteries, provided effective heat transfer thanks to the water channels at their ends. Numerical analyses compared natural and forced convection conditions; they revealed that forced convection supported by heat pipes with low thermal resistance controlled the battery temperature more effectively. Furthermore, the effect of ambient temperature on temperature homogeneity was emphasized.

Yu et al. [20] numerically investigated an air-cooled BTMS for a battery pack with a square geometry consisting of 16 cylindrical 18650 cells and reported that increasing the inlet cross-sectional area significantly reduced the maximum and average temperatures. However, it was noted that the effect of the outlet cross-sectional area on thermal performance was negligible. Furthermore, it was observed that the cells at the center of the pack reached higher temperatures compared to those on the periphery.

Hai et al. [21] reported on battery packs consisting of square and randomly arranged 18650 cylindrical cells. The study showed that the input cross-sectional area significantly reduced cell temperatures, the effect of the output geometry was limited, and cells in the middle region consistently had higher temperatures. Furthermore, it was emphasized that air velocity has a limited effect on maximum temperature up to a certain threshold value.

Ren et al. [22] developed an active cooling system incorporating a U-shaped micro heat pipe for a module consisting of 6 series-connected LiB. Within the scope of experimental and numerical studies, different environmental temperatures, air flow rates, and charge/discharge rates were evaluated. The

results showed that the heat pipe-based active cooling system achieved the lowest maximum temperature value (38.08 °C), while the passive system without a heat pipe had the highest temperature value (42.14 °C). Furthermore, it was noted that increasing the fan speed increased the temperature differences and energy consumption; it was stated that active cooling systems offer safer thermal performance, especially under high load conditions.

Yang et al. [23] designed an innovative air distribution system inspired by bionic principles for a battery pack consisting of 37 cylindrical 18650 cells. The air distribution plate, developed by drawing inspiration from spider webs and honeycomb structures, aimed to provide a more homogeneous air flow between the batteries. Test results showed that the maximum temperature was reduced from 41.9 °C to 39.8 °C. The maximum temperature was further reduced with bionic heat sinks integrated into the system; the best performance was achieved using 10 bionic heat sinks positioned at different heights. However, it was noted that the increased air speed limited homogeneity by increasing temperature differences.

Zhang et al. [24] investigated the effect of air outlet position and air velocity on the cooling performance of a battery module consisting of 21,700 cylindrical cells through a comprehensive CFD analysis. The study evaluated different flow configurations defined such that the inlet direction was perpendicular to the cooling channel and the outlet direction was parallel to the channel. The results showed that as the air velocity increased, the optimal outlet position shifted toward the inlet, and this arrangement simultaneously minimized Tmax and ΔT. Furthermore, a polynomial-based fitting function was developed between the outlet position–air velocity–thermal performance indicators, and the model was validated with experimental data. This study clearly demonstrates the critical role of outlet geometry and flow direction in the design of air-cooled BTMS.

Feng et al. [25] conducted a comprehensive optimization study for a structurally designed air-cooled LiB pack, considering both discrete and continuous variables. Parameters such as the air inlet channel angle, side surface inclination angle, and inter-cell spacing were optimized using orthogonal experimental design, response surface methodology, and a multi-objective genetic algorithm. The results showed that the system designed using discrete variables offered similar thermal performance to the model using continuous variables, but was more stable, had lower production costs, and was a more feasible solution. It was reported that the Tmax and ΔT were reduced by 5.5% and 27.7%, respectively, with the optimal configuration.

Table 1. A comparative summary of the main studies in the literature on BTMS

Reference	Method	Results and Notes
Zhang et al. (2021)	CFD-based numerical analysis; number and location of ventilation holes	Increasing the ventilation capacity has reduced Tmax and ΔT. The effect of air velocity alone is limited.
Singh et al. (2021)	Electrochemical–thermal coupled model (COMSOL)	The increase in air velocity improved heat transfer; temperature homogeneity decreased as the number of cells increased.
Alihosseini & Shafaee (2021)	Numerical + experimental; copper pipe cooling	Forced convection with copper pipe support has more effectively controlled battery temperatures.
Yu et al. (2022)	Numerical analysis; inlet–outlet cross-sectional area effect	The inlet cross-sectional area has reduced temperatures, while the effect of the outlet cross-section has remained limited.
Hai et al. (2022)	FEM-based numerical analysis; different cell arrangements	The inlet geometry is decisive; the effect of air velocity is limited up to the threshold value.
Ren et al. (2023)	Experimental + numerical; U-shaped micro heat pipe active cooling	The heat pipe system has provided the lowest Tmax value; high fan speed has increased ΔT and energy consumption.
Yang et al. (2023)	Experimental; air distribution plate	The maximum temperature has been reduced, but the high air velocity has limited homogeneity.
Zhang et al. (2024)	Numerical + experimental validation; output position optimization	Bringing the exit position closer to the inlet and increasing the air velocity minimized Tmax and ΔTmax.
Feng et al. (2024)	Numerical optimization; discrete and continuous variables	With a discrete variable design, Tmax was reduced by 5.5% and ΔT by 27.7%, providing advantages in manufacturability and stability.

The main studies conducted in the literature on air-cooled and copper pipe-supported BTMS, the methods used, and the key findings obtained are summarized in Table 1. This table was prepared to clarify the position of the current study in the literature and the research gap addressed.

When the studies presented in the literature are evaluated together (Table 1), the fundamental limitations of air-cooled BTMS come to the fore:

- Despite the reduction in maximum battery temperature, it is observed that sufficient temperature homogeneity between cells cannot be achieved. Although increasing air velocity optimization can reduce the maximum temperature, this often leads to increased temperature differences and reduced system efficiency.
- Although tube-supported cooling systems offer high thermal performance, they remain limited in practical applications due to increased system complexity, installation difficulties, and applicability issues.
- The effect of cell array geometry on cooling performance has been addressed in only a limited number of studies in the literature; in particular, the role of geometric placement in air-cooled systems has not been sufficiently investigated.

Within this scope, the presented study aims to fill the gaps in the literature by proposing an original approach. The study adopted a concave geometric cell arrangement for a battery pack consisting of a total of 28 cylindrical 18650 LiB designed in a 4 series–7 parallel (4S7P) configuration; this structure was considered together with a copper tube-supported air-cooled BTMS. The proposed system aims to provide more effective cooling compared to conventional fan-assisted active systems by combining the advantages of air cooling, namely low cost and structural simplicity, with the heat transfer enhancement effect of copper pipes.

The primary objective of this study is to maintain the operating temperature of the designed battery pack within the range of 20–40 °C and to limit the temperature difference between cells to below 5 °C. In line with this objective, cooling strategies developed using different air velocities and numbers of tubes were analyzed comparatively using both numerical and experimental methods. The findings indicate that the joint optimization of the cell array geometry and the supporting cooling elements offers an effective solution not only for reducing the maximum temperature but also for increasing temperature homogeneity. This study distinguishes itself from the existing literature by experimentally validating the concave cell arrangement and copper tube-supported air cooling approach and providing comparative analyses. The findings present a unique, applicable, and engineering-qualified solution for EVs batteries.

2. MATERIAL AND METHOD

In this study, comprehensive experimental and numerical analyses were conducted to evaluate the performance of copper pipe-assisted air-cooled thermal management systems in EVs battery packs. The battery pack consisted of a total of 28 cylindrical 18650 LiB cells arranged in a 4 series and 7 parallel (4S7P) configuration. Each cell had a nominal voltage of 3.6 V, a capacity of 3.5 Ah, and a nominal energy of 12.95 Wh, with maximum and minimum cut-off voltages set at 4.2 V and 2.5 V, respectively. Based on these characteristics, the battery module has a nominal voltage of 14.4 V, a total capacity of 24.5 Ah, and a nominal energy of approximately 352.8 Wh. In the battery pack, a concave cell arrangement geometry was adopted to improve heat dissipation between cells and increase interaction with airflow; the system was analyzed using air cooling strategies supported by copper pipes placed in different numbers and positions. In this study, the concave cell arrangement was considered as an independent design parameter. During comparative analyses, these parameters were kept constant and evaluated separately from the effects of air flow velocity and the number of copper tubes. As part of the numerical analysis, the effects of parameters such as copper pipe number, air flow velocity, and pipe placement configuration on the temperature distribution, maximum temperature value, and temperature homogeneity within the battery pack were examined separately using a detailed Computational Fluid Dynamics (CFD) model.

The primary motivation for choosing a concave cell arrangement geometry is that the heat transfer temperature gradient between the coolant and the battery cells, flow direction, velocity distribution reshaping, and inter-cell heat interaction are considered together. Increased contact with more cells in

the cold air inlet region enhances convective heat transfer due to the high temperature difference. As the flow progresses, the air temperature increases and the temperature gradient decreases; however, thanks to the concave arrangement, the fluid is directed towards the middle region, causing local velocity increases. In this geometric arrangement, copper pipes are positioned as heat transfer support elements. The tubes aim to limit the negative effects that may occur when the fluid comes into contact with more cells in the advancing regions by allowing the local temperature differences formed between the cells to spread. Therefore, the concave cell arrangement is considered a design approach that aims to achieve more balanced heat transfer not only in the region where the cold fluid first comes into contact but also throughout the flow path.

In the experimental setup, the battery cells were placed between two plates measuring 200 × 200 mm. In the concave battery arrangement, holes matching the cell layout were drilled into the upper plate, and the cells were mounted through these openings. The placement of the holes was designed to follow a concentric and staggered pattern, which not only ensured the secure mechanical assembly of the battery pack but also provided a suitable experimental infrastructure for detailed and effective analysis of thermal management performance. The cells were arranged inclined toward the geometric center of the plate. The cells at the lower section were positioned regularly, with the centers of the first row located 22.5 mm from the bottom edge and 50 mm from the lateral edges of the plate. The horizontal spacing between cells was set to 25 mm, and the cells were arranged to form an equilateral triangle pattern converging toward the center. The cells in the upper section were positioned symmetrically to the lower arrangement, with their centers progressively inclined toward the geometric center as they moved upward. This layout facilitates a compact cell placement while minimizing electrical connection lengths, thereby reducing resistance-related energy losses. Additionally, this configuration improves space utilization and is expected to contribute to enhanced mechanical stability due to its compact and symmetric structure. Within the concave battery pack, three different cooling tube configurations were designed using copper tubes of varying quantities. All copper tubes had an inner diameter of 2 mm and an outer diameter of 3 mm. The tubes were placed between the battery cells to allow air coolant flow. In the first configuration, a single copper tube was placed between each battery layer. The second configuration maintained the same placement pattern but integrated two parallel copper tubes between each battery row to increase the heat transfer surface area and improve cooling efficiency. In the third configuration, three copper tubes were installed per battery layer, maximizing the air contact surface to further enhance thermal performance. These three tube configurations were comparatively analyzed under air flow conditions, and the effects of increasing tube count on battery cooling efficiency were thoroughly evaluated. To ensure the structural integrity of the battery packs, the upper plates were mounted onto lower support plates measuring 400 mm in length and 200 mm in width. Structural reinforcement was provided by inserting U-profiled metal elements measuring 2.5 x 3.5 x 3 mm between the upper and lower plates. These profiles not only enhanced mechanical strength but also contributed significantly to the stable and secure positioning of the battery cells (Figure 1).

In this study, numerical simulations were initially performed for three different cooling pipe configurations (single-pipe, double-pipe, and triple-pipe) applied to a battery pack with a concave arrangement. These simulations were subsequently supported by experimental investigations. Based on the numerical results, the single-pipe configuration was found to be insufficient in terms of thermal management performance, while the triple-pipe configuration posed practical limitations due to its structural complexity and installation challenges. Consequently, the double-pipe configuration was selected for physical prototyping, as it offered the most balanced solution in terms of thermal effectiveness and practical applicability. An experimental setup specifically designed for the concave battery layout was constructed, and temperature distributions were observed throughout the tests. The data obtained from the experiments were utilized for the calibration and validation of the numerical models.

In this study, the thermal effects of different airflow velocities were primarily analyzed through numerical methods for battery packs with a concave cell arrangement geometry. Under a constant discharge current of 10 A—considered a critical operational condition—copper pipe-assisted air-cooled systems were modeled at airflow velocities of 5, 10, 15, and 20 m/s. CFD-based simulations were conducted to investigate the temperature distribution on the battery surface and the fluid dynamics

within the system across single-, double-, and triple-pipe cooling configurations. The flow regime was evaluated by calculating the Reynolds number [26]. Considering that the experiments were conducted within a temperature range of 25–30 °C, the thermophysical properties of air were assumed constant. Accordingly, at 25 °C, the density of air was taken as 1.184 kg/m³, the dynamic viscosity as 1.85×10^{-5} Pa·s, and the kinematic viscosity as 1.56×10^{-5} m²/s [27]. For a pipe diameter of 2 mm, the Reynolds numbers calculated for airflow velocities between 5 and 20 m/s ranged from 659 to 2636, which generally fall within the laminar flow regime. Although the critical threshold of Re = 2300 for internal pipe flows indicates a potential transition regime in some cases, laminar flow assumptions were adopted in the numerical modeling due to localized disturbances such as inlet effects, cross-sectional changes, and fan-induced flow irregularities. Air was modeled as an incompressible, constant-density, Newtonian fluid. The numerical analyses revealed that increasing airflow velocity significantly reduced the surface temperature of the battery cells and noticeably improved the cooling performance.

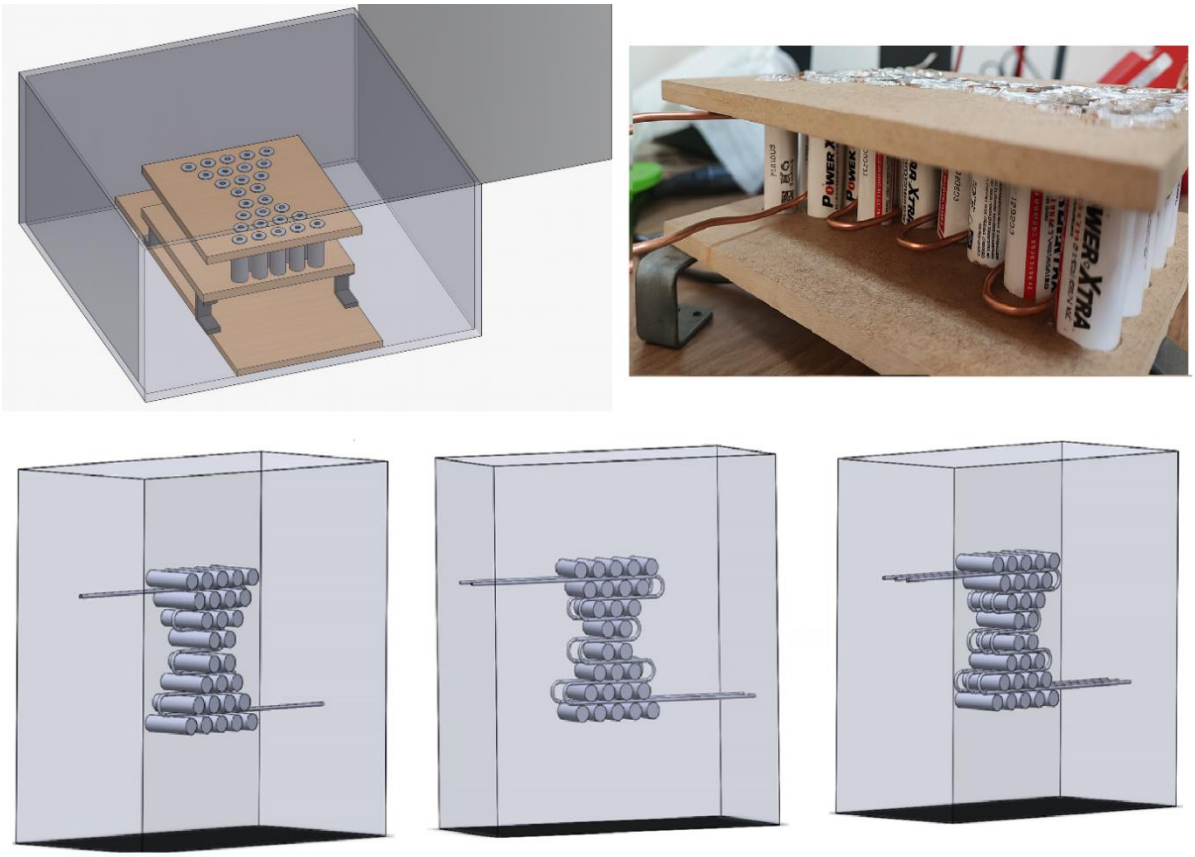


Figure 1. Concave array experimental and numerical setup.

In this study, the air flow and heat transfer behavior within the battery pack has been modeled using a three-dimensional and time-dependent (transient) CFD approach. In the numerical analyses, the governing equations—continuity, momentum, and energy equations—were solved together. The continuity equation ensures the principle of mass conservation, while the momentum equations define the behavior of air flow under forced convection conditions. The energy equation was activated in both fluid and solid regions to account for the conjugate heat transfer effects between battery cells, copper pipes, and cooling air. Conditions of continuity for temperature and heat flux are applied at fluid–solid interfaces.

To ensure the accuracy of the analyses and to optimize the computational process, the following assumptions were made: The battery pack was modeled as a constant and uniform heat-generating source; localized thermal effects of individual cells were neglected. The coolant fluid (air) were assumed to be incompressible. Connection elements and holders were excluded from the geometric model; their effects on thermal behavior and fluid dynamics were considered negligible. The conditioning environment was assumed to be adiabatic, neglecting the influence of the external environment. System

inlet conditions (pressure and temperature) were kept constant. The thermophysical properties of the fluids (density, viscosity, etc.) were assumed constant within the temperature range considered in the analysis.

To evaluate the independence of CFD solution results from the mesh and to ensure computational accuracy, a mesh independence analysis was performed using mesh structures with different element sizes and cell counts. Within the scope of this analysis, the maximum temperature, average temperature, and temperature difference values obtained for coarse, medium, and fine mesh levels were compared. The numerical results for different mesh structures are summarized in Table 2.

Table 2. Mesh independence test for numerical analysis

Mesh Level	Element Size (m)	Number of Cells (N)	Max Temperature (°C)	Average Temperature (°C)	ΔT (°C)
Coarse	0.14	968,025	41.94	35.80	16.94
Medium	0.07	2,134,308	40.78	34.80	15.78
Fine	0.035	3,777,521	40.25	34.24	15.25

As shown in Table 2, it was observed that the change in maximum temperature values remained quite limited when the mesh density was increased. The fact that the difference in Tmax between coarse and medium mesh levels and between medium and fine mesh levels is below 0.1% indicates that the numerical solution results have become independent of mesh density. However, the significant increase in the number of cells in the fine mesh structure has markedly increased the computational cost. Therefore, considering the balance between computation time and solution accuracy, the medium mesh structure has been preferred in numerical analyses. This mesh structure has been evaluated to represent the temperature distribution and maximum temperature values within the battery pack with sufficient accuracy.

Following the completion of numerical analyses, model validation was performed through experimental studies conducted under similar boundary and operating conditions. To ensure the experiments were conducted reliably and accurately, a specially designed conditioning chamber, completely isolated from external environmental influences, was established and the experiments were carried out on a battery pack with a concave cell configuration. Eight K-type thermocouples were placed at critical points to accurately measure the thermal behavior and surface temperature distribution of the battery pack (Figure 2). Additionally, four additional thermocouples were integrated into the conditioning chamber, the cooling fluid, and the inlet and outlet points of the copper pipes through which the cooling fluid passes to monitor the ambient temperature and cooling circuit performance.

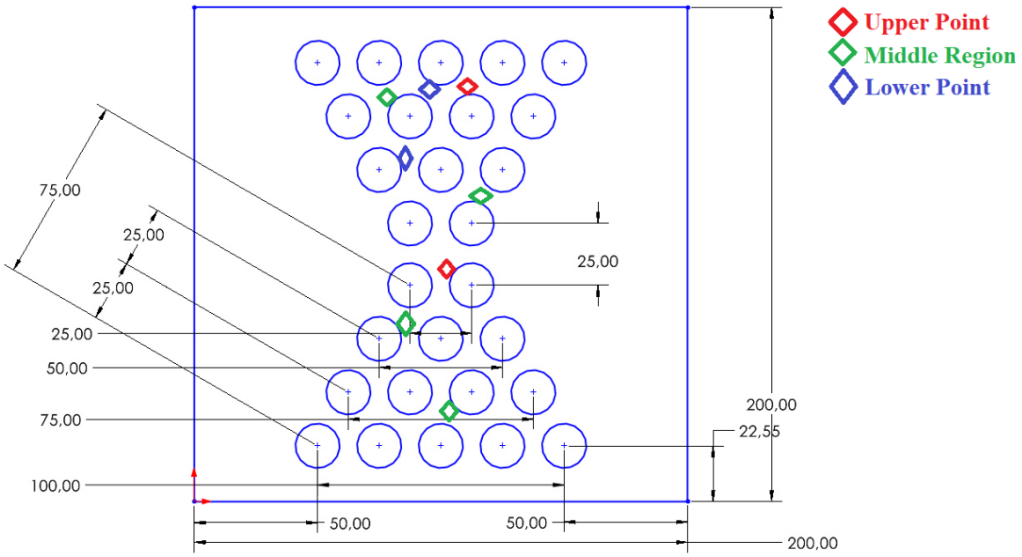


Figure 2. Schematic representation of the thermocouple placement and measurement points used in the battery pack.

Figure 2 shows the K-type thermocouple placement used in a battery pack with a concave cell arrangement configuration. Red markers represent cells in the upper region (Upper Point), green markers represent cells in the middle region (Middle Region), and blue markers represent cells in the lower region (Lower Point). The thermocouples are strategically positioned to evaluate the characteristic temperature gradients and surface temperature homogeneity across the battery pack. All temperature measurements were recorded at minute intervals throughout the experiment. The measurement points shown serve as a reference for validating the numerical model with experimental temperature data.

The experimental setup employing a copper pipe-assisted air cooling system was designed to investigate the thermal performance of the battery pack in detail and consists of several key components. Figure 3. illustrates the experimental configuration used in the physical tests and the connections of the battery pack. The environmental chamber (1), in which the battery pack is placed, ensures that experiments are conducted under stable and controlled ambient conditions. The control panel (2), which allows monitoring of current and voltage values, enables precise control of the electrical load applied to the battery pack. The adjustable discharge device (3) facilitates the application of different current loads in the range of 10–15 A, allowing thermal performance to be evaluated under various operating conditions. Thermocouples placed on the battery surface and at the air inlet and outlet points are connected to the data acquisition unit (4) to ensure accurate and continuous recording of temperature data. The fan system (5) circulates air through the cooling channels and supports heat transfer via copper pipes; airflow velocity can be adjusted via an integrated speed control circuit. The airflow is directed through ducts in which the copper pipes are embedded, promoting uniform cooling across the battery surface. All experimental data are recorded and stored in a suitable format for analysis via a data acquisition system and computer (6). This comprehensive experimental setup provides a robust and reliable infrastructure for evaluating the performance of the copper pipe-assisted air-cooled BTMS and for validating numerical simulation results.

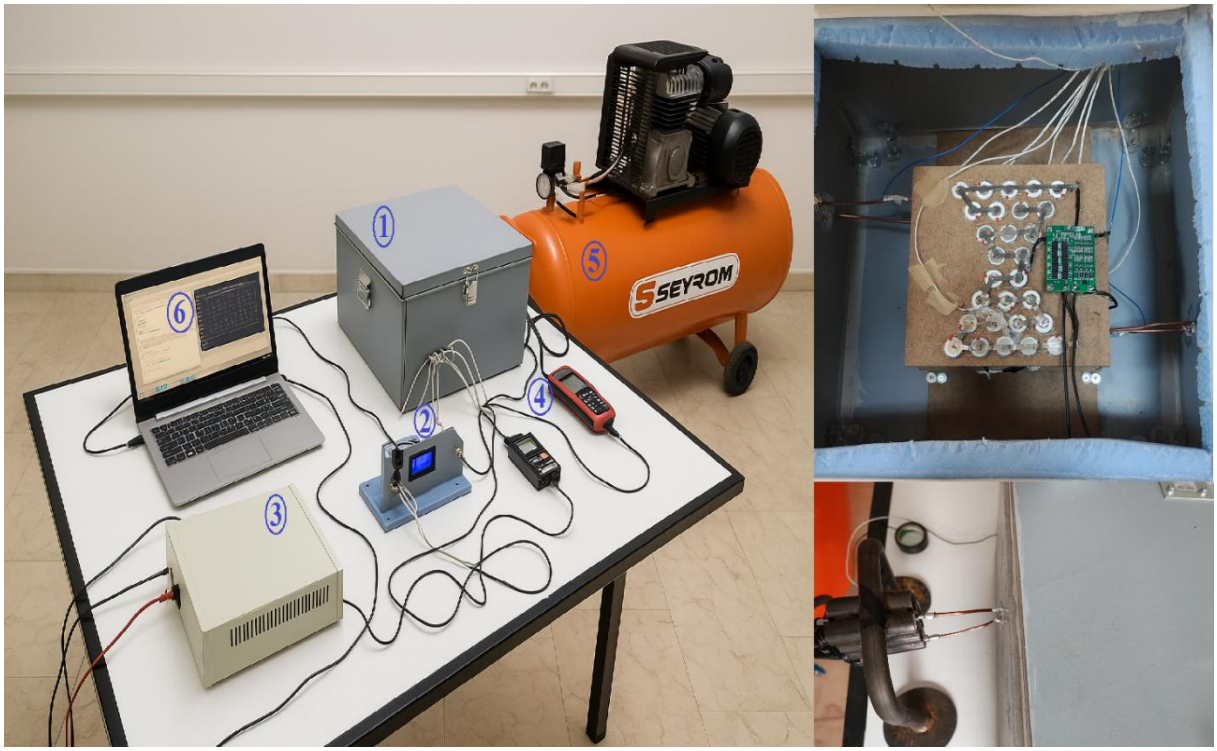


Figure 3. Experimental setup and equipment

LiB generates heat during charging/discharging due to electrochemical reactions occurring within the battery cell and energy losses caused by internal resistance. Batteries consist of four main components: the cathode (positive electrode), anode (negative electrode), separator, and electrolyte. During charging/discharging, lithium ions and electrons move between the cathode and anode; electrons are transported through the external circuit, while ions are transported through the electrolyte. During this

transport, the internal resistance in the electrode and electrolyte materials causes part of the electrical energy to be converted into Joule heat and released as heat within the cell. In this study, the total heat generated in the cells was considered solely as Joule heat and expressed by the following equation 1 [13, 28-29].

$$\dot{Q}_{generated} = I^2 R \tag{1}$$

Here, I represents the cell current (A), and *R* represents the cell internal resistance (Ω). Each 18650-type LiB cell has an internal resistance of 0.04 Ω and a discharge current of 10 A. Accordingly, the heat generation per cell examined in the study was calculated to be 4 W, and the total heat for the 28-cell pack was calculated to be 112 W. This calculated heat load has been defined as a constant and volumetric heat source for each cell in the numerical analyses. This generated heat is transferred from the cell surface to the surrounding cooling air flow through convection and conduction (Equation 2). The overall energy balance for the module is expressed as follows:

$$\dot{Q}_{generated} = \dot{Q}_{convection} + \dot{Q}_{conduction} + \dot{Q}_{storage} \tag{2}$$

Here, $\dot{Q}_{convection}$ represents heat removed by convection, $\dot{Q}_{conduction}$ represents heat removed by conduction, and $\dot{Q}_{storage}$ represents energy stored in the battery cell. This model was applied to evaluate the change in battery temperature over time and the effectiveness of the cooling system.

The numerical analyses conducted based on predefined assumptions revealed the effects of different pipe configurations and cooling air velocities on the thermal performance of the battery pack, providing a detailed assessment of the temperature distributions under critical current loads. For the high discharge current of 10 A—identified based on simulation results—model validation was performed through experimental studies conducted under similar boundary and operating conditions. In these experiments, carried out within a specially designed environmental chamber, temperature measurements were carefully monitored and thermal responses were recorded with high reliability. When the numerical and experimental results are evaluated together, the findings offer robust technical data and analyses for optimizing the cooling performance of battery packs.

3. RESULTS AND DISCUSSION

Within the scope of numerical and experimental analyses, the thermal behaviors of battery packs with concave arrangement geometry integrated with copper pipe-assisted air cooling systems were comprehensively investigated. In this configuration, the thermal management effectiveness and the uniformity of temperature distribution among cells were evaluated using one, two, and three copper pipe-assisted air channels. Air was selected as the cooling medium, and significant improvements in the system's thermal performance were achieved due to the high heat transfer capacity of the copper pipes. The findings indicate that the number and positioning of copper pipe-assisted air channels play a critical role in reducing the maximum cell temperature and minimizing temperature differentials. Consequently, the integration of copper pipe-assisted air cooling in a concave cell arrangement enhances the thermal stability of the battery pack and maintains the system within safe operating limits.

Figure 4 shows the numerical temperature distributions obtained at different air speeds (5, 10, 15, and 20 m/s) for air-cooled thermal management systems with 1, 2, and 3 copper pipes in a battery pack with a concave cell arrangement configuration. Numerical simulations were performed at the specified air speeds for each tube configuration. In the single-tube configuration, high temperature gradients formed between the cells, particularly at air speeds of 5 and 10 m/s, due to insufficient flow. As the air velocity increased to 15 m/s and above, the interaction of the air flow with the battery surface increased, and the temperature distribution became more homogeneous. In the two-pipe system, the air flow was distributed more evenly across the cell surface, resulting in a smoother temperature profile compared to the single-pipe system. The three-pipe configuration provided the most homogeneous temperature distribution even at low air speeds, but it has limitations in terms of application due to increased design complexity and cost requirements. In a single-pipe configuration, increasing the air velocity from 5 m/s to 20 m/s reduces the Tmax value from 41 °C to 35 °C and the ΔT value from 16 °C to 10 °C. In the

two-pipe configuration, the Tmax value decreases from 34 °C to 29.8 °C, and the ΔT value decreases from 9 °C to 4.8 °C. In the three-pipe configuration, the lowest temperature levels were achieved; Tmax decreased from 28.6 °C to 25.2 °C, and ΔT decreased from 3.6 °C to 0.2 °C. The overall evaluation shows that both increasing the air velocity and the number of copper pipes significantly improved temperature homogeneity throughout the battery pack. Furthermore, the two-pipe configuration operating in the 10–15 m/s air velocity range emerges as the most balanced solution when temperature homogeneity, energy efficiency, and system complexity are evaluated together.

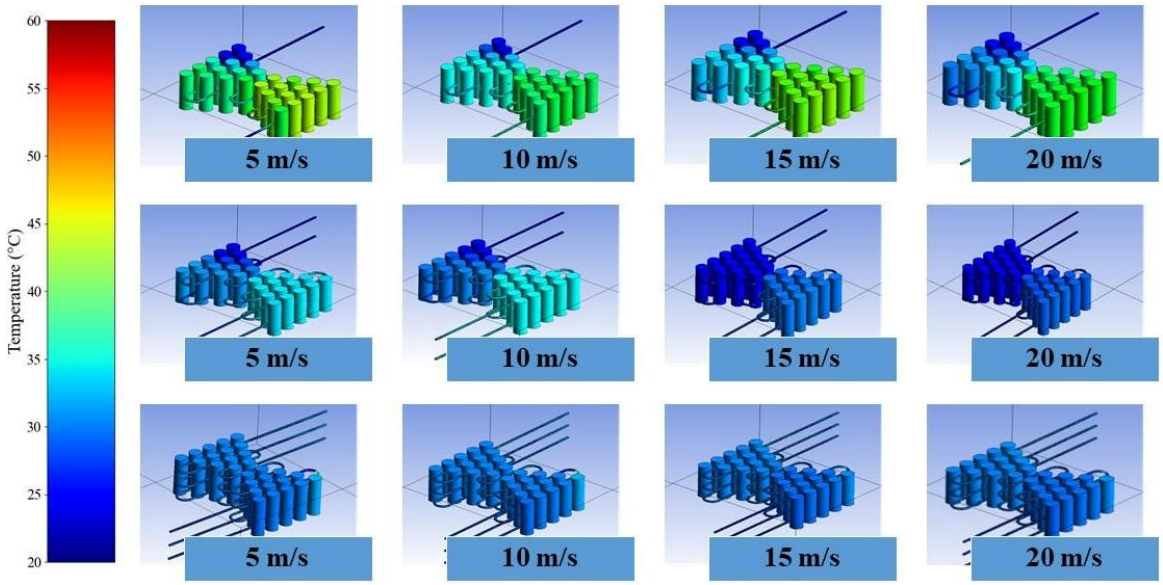


Figure 4. Comparison of Air-Cooled Copper Pipe Assisted Designs in Concave Battery Pack Geometry: CFD-Based Analysis

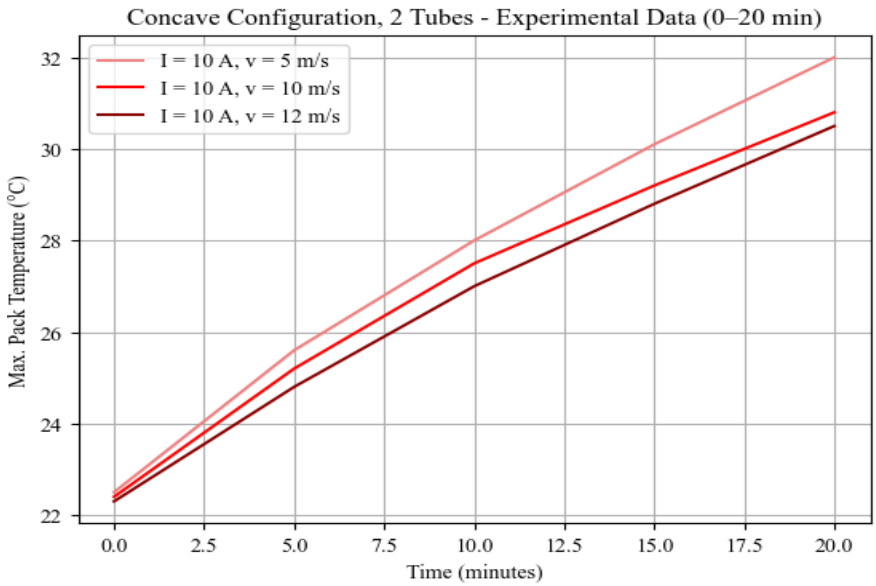


Figure 5. Temperature Distribution in a Concave Battery Pack Using a Two-Pipe Copper Pipe-Assisted Cooling Strategy

Figure 5 presents the experimentally obtained maximum battery temperatures over a 0–20 minute interval under a two-pipe copper pipe-assisted air cooling system for a battery pack with a concave cell arrangement, tested at different air velocities (5 m/s, 10 m/s, and 12 m/s). The experiments were conducted under a constant 10 A discharge current, allowing for a comparative assessment of the effects of varying air flow velocities on battery temperature evolution. The data clearly indicate that increasing the air velocity enhances the effectiveness of convective heat transfer at the battery surface. At an air

velocity of 5 m/s, the maximum battery temperature reached approximately 32 °C, whereas this value decreased to around 30.5 °C and 30 °C at 10 m/s and 12 m/s, respectively. As the air velocity increased, the slope of the temperature rise curves diminished, reflecting a significant improvement in cooling performance. These findings suggest that at lower air velocities, battery cells experience more rapid heating and approach critical thermal limits sooner; however, air velocities in the 10–12 m/s range enable more effective temperature regulation. The 10 A discharge current was selected as a representative load to monitor critical thermal thresholds. A comparison of numerical and simulation studies is provided in Table 3.

Table 3. Mesh independence test for numerical analysis

Air velocities (m/s)	Numerical Tmax (°C)	Experimental Tmax (°C)	Difference (°C)
5	34	32.1	1.9
10	31.2	30.5	0.7

Table 3 compares the numerical and experimental maximum package temperatures obtained at air velocities of 5 and 10 m/s for a two-pipe air-supported BTMS. For both air velocities, the numerical results are seen to be in agreement with the experimental data. The difference between the numerical and experimental maximum temperatures is 1.9 °C at an air flow velocity of 5 m/s, while it is 0.7 °C at an air flow velocity of 10 m/s. The decrease in the difference with increasing air velocity indicates that the numerical model more accurately represents the thermal behavior of the battery pack under more dominant forced convection conditions. It was observed that the experimentally obtained temperature data were relatively high compared to the numerical results. This can be attributed to physical factors such as irregular air flow, contact resistances, air leaks, and uncertainties related to sensor placement in the experimental setup. Nevertheless, the numerical model successfully captured the general trends in the temperature distribution, and the low temperature differences obtained confirmed the accuracy and reliability of the model. In order to evaluate the numerical and experimental maximum temperature values more intuitively, the results are compared graphically in Figure 6.

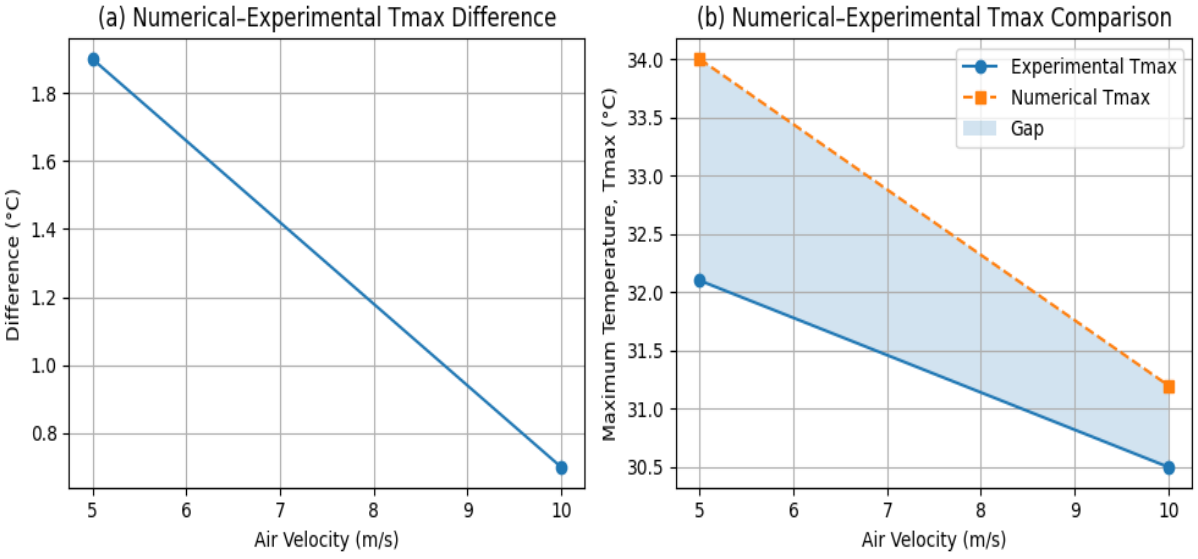


Figure 6. Comparison of numerical and experimental maximum battery temperatures for a double-tube concave configuration: (a) variation of maximum temperature difference with air velocity, (b) combined presentation of maximum temperatures.

Figure 6(a) shows that the difference between maximum temperatures decreases as air velocity increases in both numerical and experimental studies. This indicates that the numerical model represents the experimental behavior more accurately as forced convection becomes dominant. Figure 6(b) shows that the numerical and experimental maximum temperature values follow a similar decreasing trend, and the

difference between the two curves remains at limited levels. These results demonstrate that the developed numerical model can reliably represent the thermal behavior of the battery pack both quantitatively and in terms of trends.

In addition to maximum temperature assessments, the transient thermal behavior of the cooling system under a 10 A current condition was examined through temperature measurements at the cooling air inlet region and the inlet and outlet points of the copper pipe. In this context, it shows that the air inlet temperature measured through the connection element exhibited a very limited change throughout the experiment at different air speeds (5, 10, and 12 m/s). For example, at a speed of 5 m/s, the air inlet temperature changed from 22.1 °C to 22.0 °C, while at a speed of 12 m/s, this value remained constant at 20.8 °C. This situation reveals that the cooling air provided a stable inlet boundary condition to the battery pack and that the inlet conditions did not change significantly during the experiment.

In contrast, a noticeable increase in temperature values measured at the pipe inlet point was observed over time, indicating effective heat transfer from the battery cells to the pipe structure. The fact that the temperature increase at the pipe outlet remained at limited levels indicates that the heat transferred was distributed evenly along the pipe and that no sudden temperature buildup occurred between the inlet and outlet regions. For example, under conditions of 5 m/s air velocity and 10 A current, the increase in copper pipe inlet temperature from 21.2 °C to 25.1 °C ($\Delta T = 3.9$ °C) indicates that the increase in pipe outlet temperature remains quite limited (20.4–20.8 °C; $\Delta T = 0.4$ °C), indicating that the heat transported along the pipe is effectively distributed and that no temperature buildup occurs in the inlet–outlet regions. These findings demonstrate that the heat interaction between the battery pack and the coolant exhibits a stable structure not only in terms of maximum temperature values but also in terms of thermal behavior dependent on time and location.

When numerical and experimental results are evaluated together, it is observed that the concave cell arrangement with copper tube-supported air cooling creates a balanced temperature field across the battery pack. At the same air velocities and with the same copper tube configuration, the concave cell arrangement exhibits a more homogeneous temperature distribution, indicating that the observed improvement is not solely due to increased flow velocity or heat transfer surface area. Especially in two- and three-pipe configurations, the simultaneous reduction in maximum temperature and inter-cell temperature difference demonstrates a different thermal behavior compared to systems based solely on increased air velocity. It was observed that the air, which progresses along the flow direction and increases in temperature, does not create a significant temperature buildup within the pack; instead, thanks to the tube-supported structure, the temperature distribution becomes more homogeneous. These findings demonstrate that the proposed geometric structure can maintain thermal stability under different flow conditions and offers a reliable cooling solution for practical applications.

The combined evaluation of experimental and numerical analyses revealed that the number of cooling pipes and air flow velocities have a significant impact on the thermal performance of battery packs with concave cell arrangements. Investigations conducted on both single-pipe and multi-pipe copper pipe-assisted air cooling systems clearly demonstrated that two- and three-pipe configurations provide lower temperature levels and a more uniform temperature distribution compared to single-pipe systems. The numerical models exhibited a high degree of agreement with the experimental data, reinforcing the reliability of the conducted CFD analyses. Notably, the enhanced performance of multi-pipe systems at low air velocities offers substantial advantages in terms of energy efficiency and system safety. In this context, copper pipe-assisted air cooling strategies emerge as effective solutions for ensuring the long-term durability and safe operation of high-density battery packs.

The findings confirm that cooling strategies based solely on air velocity, which are widely used in the literature, have limitations in terms of temperature homogeneity. In this study, it was observed that the concave cell arrangement allows for more effective airflow within the battery pack, and the copper pipes enhance inter-cell heat spread as heat transfer support elements. While many air-cooled systems reported in the literature show an increase in temperature differences when the maximum temperature is reduced, this study demonstrates that both T_{max} and ΔT can be reduced simultaneously thanks to the tube-supported structure. It has been demonstrated that the two-pipe configuration, despite having lower system complexity compared to the three-pipe system, provides sufficient thermal performance and

offers a clear advantage over the single-pipe system. Numerical results validated by experimental data demonstrate that the proposed system is reliable not only theoretically but also in practical applications. In this respect, the study quantitatively demonstrates the performance-feasibility balance, which is often overlooked in the literature, and shows that the concave cell arrangement and pipe-supported approach are effective for air-cooled BTMS.

4. CONCLUSION AND SUGGESTIONS

In this study, the thermal performance of a battery pack with a concave cell configuration under copper pipe-assisted air cooling was investigated using experimental and numerical methods. Tmax and ΔT were quantitatively evaluated for different air velocities and copper pipe numbers (1, 2, and 3).

The results showed that the maximum battery pack temperature decreased significantly with increasing air velocity. In the experimental studies, increasing the air velocity from 5 m/s to 10 m/s in the two-tube system reduced the Tmax value from approximately 32.1 °C to 30.5 °C. Numerical analyses showed good agreement with experimental results; the numerical and experimental Tmax difference for the two-pipe configuration was determined to be 1.9 °C at 5 m/s and 0.7 °C at 10 m/s. These results confirm the accuracy and reliability of the developed CFD model.

Increasing the number of pipes had a more dominant effect on temperature homogeneity compared to air velocity. While the temperature difference in single-pipe systems remained in the range of 10–16 °C at low air velocities, this value decreased to 4.8–9 °C in two-pipe systems and 0.2–3.6 °C in three-pipe systems. Although the three-pipe configuration provides the lowest maximum temperatures and the highest temperature homogeneity, the increased system complexity and cost requirements are limiting factors for practical applications.

Overall, the two-pipe copper pipe- assisted air cooling system stands out as the most balanced and feasible solution, offering sufficient temperature reduction, acceptable temperature homogeneity, and lower system complexity. This study provides a quantitative, validated, and comparative basis for the design and optimization of pipe-supported air-cooled BTMS. In addition, the validated CFD modeling approach developed in this study is not limited to concave cell arrangements and can be extended to different battery pack geometries and cell types. This framework enables efficient thermal performance evaluation under various airflow conditions, supporting faster and more reliable BTMS design.

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Conflict of Interest Statement

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

Contributions of the Authors

This study was conceptualized by F. Akkuş and M. Z. Işık. The methodology was developed collaboratively by both authors. F. Akkuş carried out the software implementation, investigation process, data curation, visualization, and prepared the original draft of the manuscript. M. Z. Işık was responsible

for validation, review and editing of the manuscript, supervision of the research process, project administration, and funding acquisition. All authors have read and approved the final version of the manuscript.

REFERENCES

[1] S. S. Alrwashdeh, "Energy sources assessment in Jordan", *Results in Engineering*, c. 13, s. 100329, Mar. 2022, doi: 10.1016/j.rineng.2021.100329.

[2] Ö. Alkan ve Ö. K. Albayrak, "Ranking of renewable energy sources for regions in Turkey by fuzzy entropy based fuzzy COPRAS and fuzzy MULTIMOORA", *Renewable Energy*, c. 162, ss. 712-726, Ara. 2020, doi: 10.1016/j.renene.2020.08.062.

[3] T.-Z. Ang, M. Salem, M. Kamarol, H. S. Das, M. A. Nazari, ve N. Prabaharan, "A comprehensive study of renewable energy sources: Classifications, challenges and suggestions", *Energy Strategy Reviews*, c. 43, s. 100939, Eyl. 2022, doi: 10.1016/j.esr.2022.100939.

[4] "Statistical Review of World Energy 2022", 2022, [Çevrimiçi]. Erişim adresi: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf

[5] A. Lahnaoui, C. Wulf, H. Heinrichs, ve D. Dalmazzone, "Optimizing hydrogen transportation system for mobility by minimizing the cost of transportation via compressed gas truck in North Rhine-Westphalia", *Applied Energy*, c. 223, ss. 317-328, Ağu. 2018, doi: 10.1016/j.apenergy.2018.03.099.

[6] A. A. Pesaran, "Battery thermal models for hybrid vehicle simulations", Journal of Power Sources, c. 110, sy 2, ss. 377-382, Ağu. 2002, doi: 10.1016/S0378-7753(02)00200-8.

[7] Modern Electric, Hybrid Electric, and Fuel Cell Vehicles, Third Edition. CRC Press, 2018. doi: 10.1201/9780429504884.

[8] Y. Lyu, A. R. M. Siddique, S. H. Majid, M. Biglarbegian, S. A. Gadsden, ve S. Mahmud, "Electric vehicle battery thermal management system with thermoelectric cooling", *Energy Reports*, c. 5, ss. 822-827, Kas. 2019, doi: 10.1016/j.egyr.2019.06.016.

[9] X. Li, Z. Wang, ve L. Zhang, "Co-estimation of capacity and state-of-charge for lithium-ion batteries in electric vehicles", *Energy*, c. 174, ss. 33-44, May. 2019, doi: 10.1016/j.energy.2019.02.147.

[10] X. Han, M. Ouyang, L. Lu, ve J. Li, "A comparative study of commercial lithium ion battery cycle life in electric vehicle: Capacity loss estimation", *Journal of Power Sources*, c. 268, ss. 658-669, Ara. 2014, doi: 10.1016/j.jpowsour.2014.06.111.

[11] X. Xu, W. Li, B. Xu, ve J. Qin, "Numerical study on a water cooling system for prismatic LiFePO4 batteries at abused operating conditions", *Applied Energy*, c. 250, ss. 404-412, Eyl. 2019, doi: 10.1016/j.apenergy.2019.04.180.

[12] J. Xu, C. Lan, Y. Qiao, ve Y. Ma, "Prevent thermal runaway of lithium-ion batteries with minichannel cooling", *Applied Thermal Engineering*, c. 110, ss. 883-890, Oca. 2017, doi: 10.1016/j.applthermaleng.2016.08.151.

[13] Z. Rao ve S. Wang, "A review of power battery thermal energy management", *Renewable and Sustainable Energy Reviews*, c. 15, sy 9, ss. 4554-4571, Ara. 2011, doi: 10.1016/j.rser.2011.07.096.

[14] L. Fan, J. M. Khodadadi, ve A. A. Pesaran, "A parametric study on thermal management of an air-cooled lithium-ion battery module for plug-in hybrid electric vehicles", *Journal of Power Sources*, c. 238, ss. 301-312, Eyl. 2013, doi: 10.1016/j.jpowsour.2013.03.050.

[15] Y. Huang vd., "A novel approach for Lithium-ion battery thermal management with streamline shape mini channel cooling plates", *Applied Thermal Engineering*, c. 157, s. 113623, Tem. 2019, doi: 10.1016/j.applthermaleng.2019.04.033.

[16] Z. Ling vd., "Review on thermal management systems using phase change materials for electronic components, Li-ion batteries and photovoltaic modules", *Renewable and Sustainable Energy Reviews*, c. 31, ss. 427-438, Mar. 2014, doi: 10.1016/j.rser.2013.12.017.

[17] F. Zhang, P. Wang, ve M. Yi, "Design optimization of forced air-cooled lithium-ion battery module based on multi-vents", *Journal of Energy Storage*, c. 40, s. 102781, Ağu. 2021, doi: 10.1016/j.est.2021.102781.

[18] L. K. Singh, G. Mishra, A. K. Sharma, ve A. K. Gupta, "A numerical study on thermal management of a lithium-ion battery module via forced-convective air cooling", *International Journal of Refrigeration*, c. 131, ss. 218-234, Kas. 2021, doi: 10.1016/j.ijrefrig.2021.07.031.

[19] A. Alihosseini ve M. Shafaee, "Experimental study and numerical simulation of a Lithium-ion battery thermal management system using a heat pipe", *Journal of Energy Storage*, c. 39, s. 102616, Tem. 2021, doi: 10.1016/j.est.2021.102616.

[20] Q. Yu, A. Abidi, M. Z. Mahmoud, E. Hasani Malekshah, ve H. Ş. Aybar, "Numerical evaluation of the effect of air inlet and outlet cross-sections of a lithium-ion battery pack in an air-cooled thermal management system", *Journal of Power Sources*, c. 549, s. 232067, Kas. 2022, doi: 10.1016/j.jpowsour.2022.232067.

[21] T. Hai, A. Abidi, A. M. Abed, J. Zhou, E. H. Malekshah, ve H. Ş. Aybar, "Three-dimensional numerical study of the effect of an air-cooled system on thermal management of a cylindrical lithium-ion battery pack with two different arrangements of battery cells", *Journal of Power Sources*, c. 550, s. 232117, Ara. 2022, doi: 10.1016/j.jpowsour.2022.232117.

[22] R. Ren, Y. Zhao, Y. Diao, ve L. Liang, "Experimental study on the bottom liquid cooling thermal management system for lithium-ion battery based on multichannel flat tube", *Applied Thermal Engineering*, c. 219, s. 119636, Oca. 2023, doi: 10.1016/j.applthermaleng.2022.119636.

[23] W. Yang, F. Zhou, X. Chen, K. Li, ve J. Shen, "Thermal performance of honeycomb-type cylindrical lithium-ion battery pack with air distribution plate and bionic heat sinks", *Applied Thermal Engineering*, c. 218, s. 119299, Oca. 2023, doi: 10.1016/j.applthermaleng.2022.119299.

[24] S. Zhang, F. Nie, J. Cheng, H. Yang, ve Q. Gao, "Optimizing the air flow pattern to improve the performance of the air-cooling lithium-ion battery pack", *Applied Thermal Engineering*, c. 236, s. 121486, Oca. 2024, doi: 10.1016/j.applthermaleng.2023.121486.

[25] X.-H. Feng, Z.-Z. Li, F.-S. Gu, ve M.-L. Zhang, "Structural design and optimization of air-cooled thermal management system for lithium-ion batteries based on discrete and continuous variables", *Journal of Energy Storage*, c. 86, s. 111202, May. 2024, doi: 10.1016/j.est.2024.111202.

[26] K. Chen vd., "Design of Parallel Air-Cooled Battery Thermal Management System through Numerical Study", *Energies*, c. 10, sy 10, s. 1677, Eki. 2017, doi: 10.3390/en10101677.

[27] Y. A. Çengel, M. A. Boles, ve M. Kanoglu, Thermodynamics: an engineering approach, Ninth edition. New York, NY: McGraw-Hill Education, 2019.

[28] Y. Fan, Y. Bao, C. Ling, Y. Chu, X. Tan, ve S. Yang, "Experimental study on the thermal management performance of air cooling for high energy density cylindrical lithium-ion batteries", *Applied Thermal Engineering*, c. 155, ss. 96-109, Haz. 2019, doi: 10.1016/j.applthermaleng.2019.03.157.

[29] M. Malik, I. Dincer, M. A. Rosen, M. Mathew, ve M. Fowler, "Thermal and electrical performance evaluations of series connected Li-ion batteries in a pack with liquid cooling", *Applied Thermal Engineering*, c. 129, ss. 472-481, Oca. 2018, doi: 10.1016/j.applthermaleng.2017.10.029.