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NUMERICAL INVESTIGATION OF THE THERMAL MANAGEMENT OF 18650 LITHIUM-ION BATTERIES USING HEXAGONAL BORON NITRIDE-FILLED EPOXY COMPOSITE UNDER VARYING AIRFLOW VELOCITIES

HEKSAGONAL BOR NİTRÜR DOLDURULMUŞ EPOKSİ KOMPOZİT KULLANILARAK 18650 LİTYUM İYON PİLLERİN DEĞİŞKEN HAVA AKIŞ HIZLARINDA TERMAL YÖNETİMİNİN SAYISAL ARAŞTIRMASI

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ABSTRACT

18650 lithium-ion batteries require thermal management to prevent thermal runaway and ensure safe operation. This study uses computational fluid dynamics to compare the thermal performance of pure epoxy resin and a hexagonal boron nitride (h-BN)-doped epoxy composite in a battery module. Analyses have been conducted at an ambient temperature of 25°C and air inlet velocities of 2, 3, and 4 m/s. Temperature distributions, maximum temperatures, and outlet temperatures have been evaluated. The h-BN-doped epoxy reduced the maximum temperatures across all operating conditions due to its high thermal conductivity. At 2 m/s, the maximum temperature decreased from 48.08°C with pure epoxy to 38.8°C with the epoxy/h-BN composite. In the air-only control case, the predicted temperature exceeded 4600°C, indicating insufficient heat dissipation. Overall, the composite improved temperature uniformity and supported safer, more reliable battery operation.

Keywords: 18650 Lithium-ion battery, thermal management, hexagonal boron nitride, epoxy composite, computational fluid dynamics

ÖZET

18650 lityum iyon piller, termal kaçağı önlemek ve güvenli çalışmayı sağlamak için termal yönetime ihtiyaç duymaktadır. Bu çalışma, bir batarya modülündeki saf epoksi reçine ile hekzagonal bor nitrür (h-BN) katkılı epoksi kompozitin termal performansını karşılaştırmak amacıyla hesaplamalı akışkanlar dinamiği yöntemini kullanmaktadır. Analizler, 25°C ortam sıcaklığında ve 2, 3 ve 4 m/s hava giriş hızlarında gerçekleştirilmiştir. Sıcaklık dağılımları, maksimum sıcaklıklar ve çıkış sıcaklıkları değerlendirilmiştir. h-BN katkılı epoksi, yüksek termal iletkenliği sayesinde tüm çalışma koşullarında maksimum sıcaklıkları düşürmüştür. 2 m/s hızında maksimum sıcaklık, saf epoksideki 48.08°C seviyesinden epoksi/h-BN kompoziti ile 38.8°C'ye gerilemiştir. Sadece havanın kullanıldığı kontrol durumunda tahmin edilen sıcaklık 4600°C'yi aşarak ısı atımının yetersiz kaldığını göstermiştir. Genel olarak kompozit malzeme, sıcaklık homojenliğini iyileştirmiş ve daha güvenli, daha güvenilir batarya operasyonunu desteklemiştir.

Anahtar Kelimeler: 18650 Lityum-iyon pil, termal yönetim, altıgen bor nitrür, epoksi kompozit, hesaplamalı akışkanlar dinamiği

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INTRODUCTION

Lithium-ion batteries are widely used in electric vehicles, portable electronics, and energy storage systems due to their advantages, such as high energy density, long cycle life, and low self-discharge rates (Ramalingam et al., 2025). 18650-type cylindrical cells are frequently preferred in multi-cell battery systems due to their compact structure and standardized dimensions (Casado et al., 2025). However, the heat accumulation that occurs during the use of battery systems both reduces efficiency and increases safety risks (Bugryniec et al., 2025). Overheating can lead to serious consequences such as capacity loss, electrolyte deterioration, and even thermal runaway. Therefore, it is important to ensure effective heat management during the operation of batteries (Gong et al., 2025). Traditional cooling methods are often inadequate, and the effect of filler materials on thermal performance is particularly prominent in high-density battery packs (Chen et al., 2024). In this context, epoxy-based composite materials are suitable for use in terms of thermal conductivity, as well as providing electrical insulation and structural support (Han et al., 2025). Adding high thermal conductivity additives such as hexagonal boron nitride (h-BN) to epoxy can significantly increase the thermal properties of these materials (Li et al., 2022).

There are many academic papers on this subject in the literature. Some of them are as follows. Zhang et al. (2021) designed two different batteries to increase Li-ion batteries' thermal and mechanical strength (Zhang et al., 2021). First, they modeled a Li-ion battery using only silicon; then, they created a second battery model containing an h-BN/silicone rubber (SR) composite by adding hexagonal boron nitride (h-BN) to silicon. They examined the chemical structures, thermal properties, and compressive stress-strain relationships of the batteries they modeled. As a result of their experiments, they observed that silicone rubber exhibited higher thermal conductivity and improved mechanical properties when combined with h-BN. They measured the thermal conductivity coefficient, k, of the h-BN/SR-filled battery as 0.58 W/mK at a 30% filling ratio, which was determined to be 3.4 times higher than that of the pure silicone-filled battery. They also reported the compressive strength of the h-BN/SR composite as 4.27 MPa, which was 6.7 times higher than that of pure silicone rubber.

Experimental findings also showed that the peak battery temperature decreases when the h-BN/SR composite is used in the battery thermal management system. Rodrigues et al. (2016) investigated the effects of using composite materials to increase the operating capacity of Li-ion batteries at high temperatures, from room temperature to 150 °C (Rodrigues et al., 2016). They used a stoichiometric mixture of hexagonal boron nitride (h-BN), piperidinium-based ionic liquid, and lithium salt as the composite structure. When they tested the new battery, they observed that it provided stable performance for approximately 600 cycles at 120 °C. With this finding, they found that the total capacity loss was reduced by 3%. They also reported that their developed battery operated efficiently in the 24 to 150 °C temperature range. Feng et al. (2022) prepared an aluminum oxide (Al_2O_3)-based structure with a multiscale filling method and combined it with epoxy resin (EP) to form composites with high thermal conductivity (Feng et al., 2022). They examined the thermal properties of the composite structures they developed. As a result of their analysis, they observed that the filled composites offered 130 times higher thermal conductivity compared to pure epoxy resin. Mussa et al. (2020) investigated the use of hexagonal boron nitride (h-BN) composites as anode materials that can be used at high temperatures in Li-ion batteries (Mussa et al., 2020). According to their results, they observed that the use of h-BN increased the thermal stability of Li-ion batteries. Rahman et al. (2019) prepared a synthesis of boron nitride nanotubes to prevent thermal stress and short circuits due to overheating in Li-ion batteries (Rahman et al., 2019). They used this synthesis as a filling material in the battery. As a result of their examinations, they observed that the thermal conductivity of these filled batteries increased and showed higher resistance to overheating.

Zhou et al. (2022) investigated the thermal properties of an insulation material used in Li-ion batteries at low temperatures (Zhou et al., 2022). Their tests measured the properties of composite materials formed by ceramics, such as aluminum nitride (AlN) and silicon carbide (SiC) with epoxy resin. According to their results, these composites offered better thermal conductivity at low temperatures than pure epoxy. They also stated that AlN/epoxy and SiC/epoxy composites exhibited dynamic mechanical properties and had low thermal expansion coefficients. Considering these advantages, they stated that these composites have potential Li-ion battery applications. Angizi et al. (2024) investigated the potential of Li-ion batteries to increase energy storage efficiency (Angizi et al., 2024). Their evaluations showed that integrating hexagonal boron nitride (h-BN) nanomaterials into Li-ion batteries increased the safety, lifetime, and electrochemical performance of components such as electrodes, electrolytes, and separators. They summarized the fundamental properties of h-BN, challenges, and the current strategies to overcome them. They also explained the functions of h-BN in battery components and the molecular mechanisms that contribute to performance improvements. Bergman (2024) developed a composite with high thermal conductivity to reduce the

risk of thermal runaway in Li-ion batteries (Bergman, 2024). He produced this composite using an infused epoxy matrix and 75% hexagonal boron nitride (h-BN) particles. He measured the density of the composite as 1.81 g/cm³ and its thermal conductivity in the range of 6.1–6.9 W/mK. He used this material in a prototype he designed for a Li-ion battery, which exhibits electrical insulation and high mechanical strength properties. As a result of the test he conducted, he confirmed that the composite he developed could withstand temperatures up to 300 °C. Aydin et al. (2017) produced innovative hexagonal boron nitride (hBN) and polyacrylonitrile (PAN) based composite nanofibers for rechargeable Li-ion battery applications by the electro spraying method (Zhang et al., 2016). They characterized the nanofibers produced using FT-IR, TGA, XRD, and SEM techniques, depending on the hBN content. They investigated the effects of hBN/PAN ratios on fiber diameter, porosity, and liquid electrolyte absorption capacity. They showed that the loaded nanofibers provided the highest ionic conductivity at 10^{3} S cm^{1} and offered high electrochemical stability up to 4.7 V. They reported that the produced Li//%10 hBN/PAN//$LiCO_2$ cell provided 144 mAh g^{1} discharge capacity and 92.4% capacity retention. Their findings suggested that hBN/PAN fiber electrolytes could be a potential separator material in Li-ion batteries. Zhang et al. (2016) investigated using h-BN as an electrode material in lithium-ion batteries (Aydın et al., 2017). As a result of their electrochemical analysis, they determined that h-BN has good cycling stability. Chandran et al. (2020) studied the mechanical, electrical, and thermal properties of hexagonal boron nitride (h-BN) and graphene as nanofillers in epoxy (Chandran et al., 2020). As a result of their studies with numerical methods, they found that the thermal conductivity and thermal diffusivity of the epoxy composite with h-BN added increased by 27.4% and 75.5%, respectively. As a result of the analyses made for graphene/epoxy under the same conditions, they found that the thermal conductivity and thermal diffusivity increased by 5.46% and 14.2%, respectively. According to these data, they concluded that h-BN is an excellent filler with high thermal conductivity and low electrical conductivity.

In this study, the thermal effects of pure epoxy and h-BN doped epoxy composite filler materials on the 18650-type lithium-ion battery system have been investigated by the computational fluid dynamics (CFD) method. Under different air inlet velocities (2 m/s, 3 m/s, 4 m/s), the cooling performance of both materials has been compared; evaluations have been made on the outlet temperatures and temperature distributions. The findings reveal the extent to which filler material selection is decisive regarding thermal balance and safety in battery systems.

MATERIAL AND METHODS

System Design

The battery pack and airflow geometry used in this study are based on the dimensions of 18650-type cylindrical lithium-ion battery cells, which are widely used in industry. The definition of 18650 indicates that the cell is approximately 18 mm in diameter and 65 mm in length. Accordingly, 24 cylindrical cells, each with a diameter of 18 mm, have been placed in the simulation model, and the analyses have been built on this placement.

The design has also been created with cell geometry. A total of 54 air channels, each with a diameter of 5 mm, have been used for the air to enter the system. In the outlet area, a single outlet channel with a diameter of 50 mm has been designed to transfer the flow efficiently to the outside. Designing multiple inlet channels with small diameters and a single outlet channel with a large diameter ensures a more homogeneous air flow distribution between the cells. This structure reduces temperature differences within the system, increases cooling performance, and reduces the risk of overheating. Dimensional technical drawings of the inlet and outlet regions and the positioning and layout of the 18650 battery cells and nickel-based cathode materials in the simulation domain are presented in Figures 1 and 2, respectively.

Materials

This paper evaluated the thermal performances of different filling materials placed around the battery cells. Three different materials have been used in the numerical analyses:

- Epoxy + h-BN doped composite material (Epoxy 1)
- Pure epoxy resin (Epoxy 2)
- Air as a reference medium (Control group)

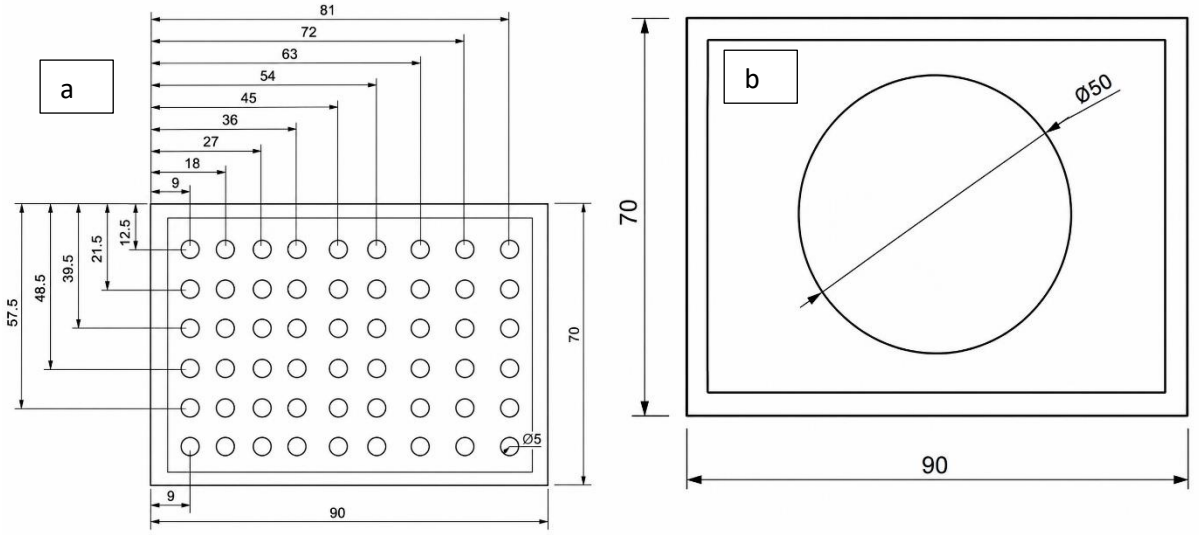

Figure 1. a. Inlet Channel, **b.** Outlet Channel

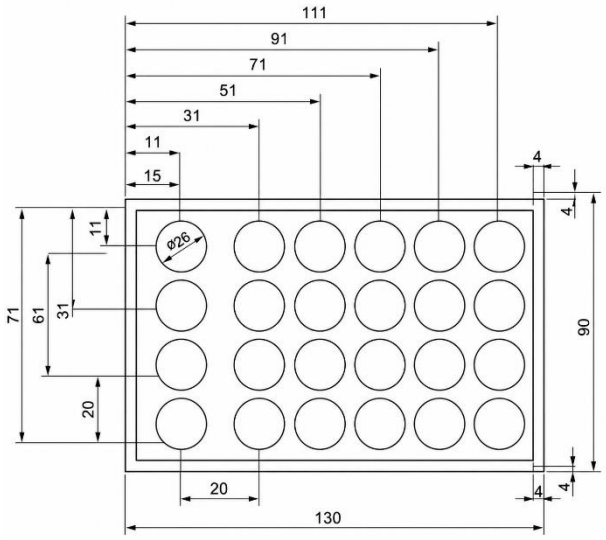

Figure 2. Layout of 18650 Battery Cells and Nickel-Based Cathode Materials in the Simulation Domain

Epoxy 1 is a composite structure enriched with hexagonal boron nitride (h-BN) doped with high thermal conductivity. This doped material aims to improve the cooling performance by increasing the heat transfer capacity. Epoxy 2 is pure resin without additives and has been evaluated as a basic benchmark. Air has been used as a reference medium in comparative analyses. This medium has been modeled to observe the system's temperature behavior during an analysis without filling material. The air-only configuration was considered solely as a reference case to demonstrate the importance of thermally conductive filler materials and does not represent a practical battery pack design. Basic thermophysical properties such as density (ρ), thermal conductivity (λ), and specific heat capacity (c_p) of each material are given in the table below.

Table 1. Materials and Specifications

Specification	**Epoxy +h-BN**	**Pure Epoxy Resin**	**Air (Control)**
Density (kg/m³)	2100	1184	2722
Thermal Conductivity (W/m·K)	3.5	0.0257	0.2
Specific Heat Capacity (J/Kg.K)	740	1006	1200

Meshing

The mesh structure used in finite element analyses is an important factor in terms of the accuracy, stability, and computational time of the numerical solution. Especially in fluid–solid interaction systems, the quality of the mesh structure directly affects the accurate prediction of temperature and velocity distributions. A low-quality or insufficiently refined mesh may lead to convergence problems and deviations in the numerical results.

A three-dimensional hybrid unstructured mesh was generated in CFD software for thermal analysis of the 18650 lithium-ion battery modules. The computational domain consisted of both solid regions, including battery cells and epoxy composite, and the fluid region through which the cooling air flowed. The generated mesh consisted of approximately 1 million elements, including tetrahedral, hexahedral, and wedge elements. The maximum, average, and minimum element sizes were 1.0 mm, 0.875 mm, and 0.7 mm, respectively. To improve the accuracy of the near-wall solution, five inflation layers were generated on all battery surfaces using the smooth transition inflation algorithm with a growth rate of 1.2. Furthermore, local mesh refinement was applied around the battery cell surfaces, the battery–epoxy composite interfaces, and the inlet and outlet regions, where high temperature and velocity gradients were expected, thereby improving mesh quality in these critical regions. The mesh was generated using the CFD physics preference and solver preference settings, and the span angle center option was set to fine to improve surface discretization quality. Figure 3 presents the overall computational mesh together with detailed close-up views of the battery surface, the battery–epoxy composite interface, the computational mesh around the battery cells, the locally refined critical regions, and the near-wall inflation layers.

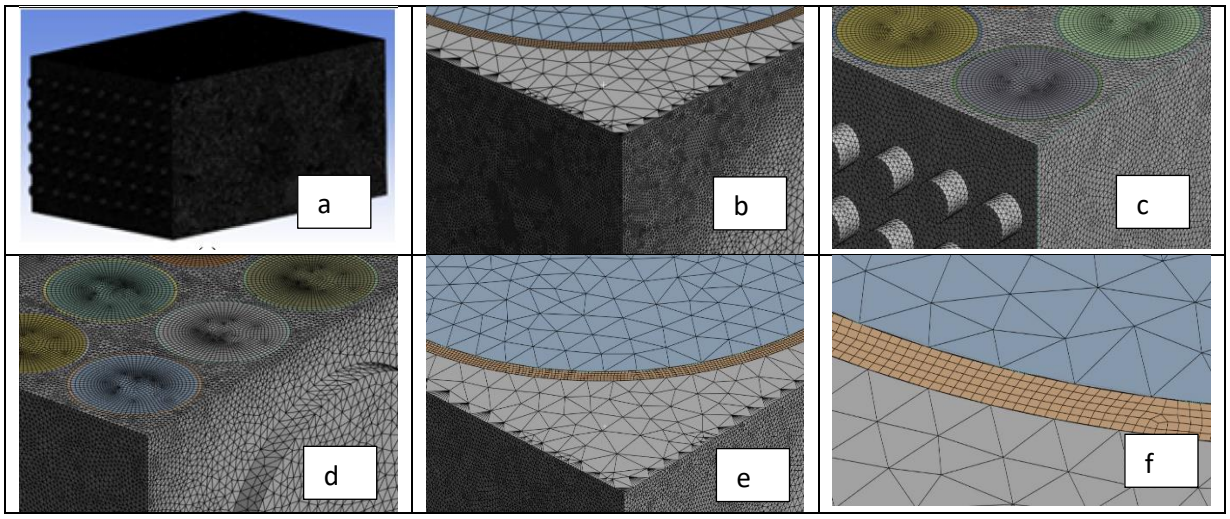

Figure 3. a. Overall Computational Mesh of the 18650 Lithium-Ion Battery Module, **b.** Close-up View of the Battery Surface and Battery–Epoxy Composite Interface, **c.** Close-up View of the Computational Mesh around the Battery Cells (top view), **d.** Detailed View of the Locally Refined Mesh Around the Battery Cells and Epoxy Composite, **e.** Close-up View of the Inflation Layers Generated on the Battery Surface, and **f.** Detailed View of the Near-Wall Inflation Layers at the Battery–Epoxy Composite Interface

A mesh independence study was performed to verify that the numerical results were independent of the computational mesh and to determine the most appropriate mesh configuration for the simulations. For this purpose, four different mesh configurations were generated and analyzed under identical boundary conditions. In all cases, an inlet air velocity of 2 m/s was applied, and the epoxy + h-BN composite was used as the filler material. Based on the results, the effect of mesh density on the maximum battery temperature was evaluated, and the mesh that provided the best balance between computational accuracy and efficiency was selected for all subsequent simulations. The results of the mesh independence study are presented in Table 2.

As shown in Table 2, the percentage difference between the fine and very fine meshes is only 0.03%. Therefore, considering the balance between computational accuracy and computational cost, the fine mesh was selected for all subsequent simulations.

Table 2. Results of the Mesh Independence Study

Mesh	Number of Elements	Maximum Temperature (°C)	Difference (%)
Coarse	486,354	39.12	-
Medium	812,945	38.89	0.59
Fine	1,126,768	38.80	0.23
Very Fine	1,703,584	38.77	0.03

To further evaluate the adequacy of the near-wall mesh resolution, the wall y^+ distribution was examined on the battery surfaces, as illustrated in Figure 4. The obtained wall y^+ values remained below 2.0 throughout the computational domain, with most battery surfaces exhibiting values close to unity. These results satisfy the recommended near-wall resolution requirements for the SST k–ω turbulence model, ensuring that the viscous sublayer is properly resolved. Consequently, the adopted mesh provides sufficient near-wall accuracy for reliable prediction of conjugate heat transfer and forced convection within the battery module.

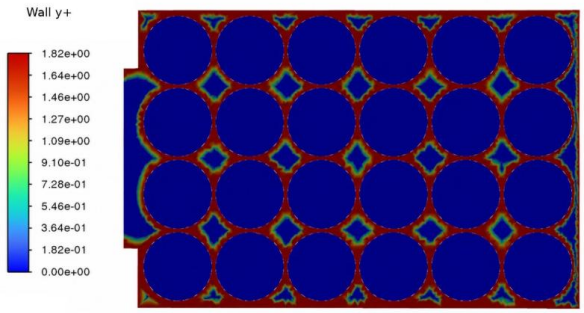

Figure 4. Distribution of Wall y^+ Values on the Battery Surfaces

Computational Fluid Dynamics (CFD) Analysis

Computational Fluid Dynamics (CFD) is a numerical analysis method used to model and analyze the physical behavior of fluids, including velocity, pressure, temperature, and density distributions. By solving the governing equations, such as the Navier–Stokes, energy, and turbulence equations, CFD enables the prediction of fluid flow and heat transfer characteristics under various operating conditions without the need for prototype manufacturing. Therefore, CFD has become an indispensable tool in many engineering applications, particularly in the automotive, aerospace, and energy industries (Sorgente et al., 2022). In lithium-ion battery technology, CFD is widely employed to predict thermal behavior, evaluate cooling performance, optimize thermal management systems, and improve battery safety and service life (Kepekci & Ağca, 2023).

The Reynolds numbers corresponding to the inlet air velocities were calculated using the battery diameter (18 mm) as the characteristic length and the kinematic viscosity of air at 25 °C ($\nu = 1.56 \times 10^{-5}$ m²/s). The calculated Reynolds numbers and the corresponding flow regimes are summarized in Table 3.

Table 3. Air Inlet Velocities, Reynolds Numbers, and Flow Regimes

Air Inlet Velocity (m/s)	Characteristic Length (m)	Reynolds Number (Re)	Flow Regime
2	0.018	2308	Transitional
3	0.018	3462	Transitional
4	0.018	4615	Transitional

Although the calculated Reynolds numbers indicate a transitional flow regime, the airflow around the cylindrical battery cells exhibits flow separation, wake formation, local recirculation, and significant near-wall thermal gradients.

Therefore, the SST k–ω turbulence model was adopted for its superior capability to predict near-wall flow behavior, adverse pressure gradients, separated flows, and conjugate heat transfer compared with conventional two-equation turbulence models (Kepekci & Ağca, 2024). Consequently, the SST k–ω model was considered the most appropriate turbulence model for the present battery thermal management simulations.

The analyses were carried out at a constant ambient temperature of 25°C using two different filler materials (epoxy + h-BN and pure epoxy). Three inlet air velocities (2, 3, and 4 m/s) were considered, with air used as the cooling fluid in all simulations. All analyses were performed under steady-state conditions with 20,000 iterations.

In addition, air was employed as a third medium (control case) only under the 2 m/s inlet velocity condition to establish a comparative reference. In this configuration, the filler material was completely removed, leaving only the air domain to evaluate the battery module's thermal behavior under passive cooling conditions. This control configuration was intentionally limited to the 2 m/s case because the excessive temperature rise and insufficient heat transfer observed under these conditions indicated that extending it to higher inlet velocities would not provide additional engineering significance. Therefore, the control case was included solely to establish a comparative baseline for evaluating the effectiveness of the thermally conductive filler materials.

The boundary conditions were defined to accurately represent the airflow within the battery module. Air entered the computational domain through multiple circular inlet channels located on the front surface and exited through a single outlet channel positioned on the rear surface. A constant-velocity inlet and a pressure-outlet boundary condition were applied throughout the simulations. The airflow direction was defined from the inlet toward the outlet to achieve a homogeneous cooling distribution between the battery cells. The locations of the inlet and outlet regions, together with the applied boundary conditions, are illustrated in Figure 5.

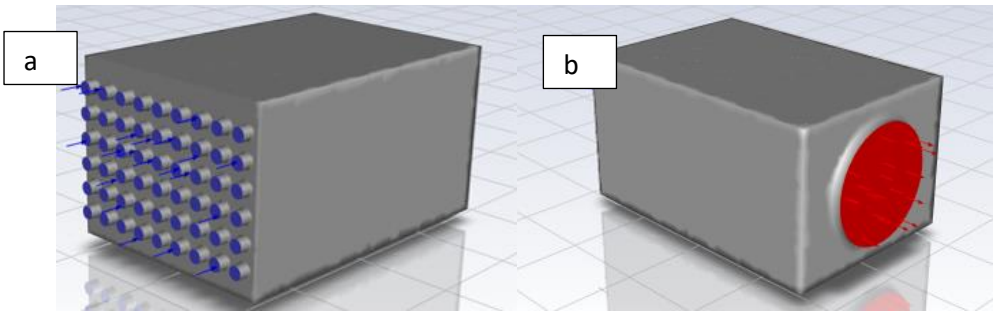

Figure 5. a. Inlet Surface, **b.** Outlet Surface

RESULTS

Comparison of Temperature Distributions Depending on Material Type Under 2 m/s Air Velocity

This section compares the temperature distributions obtained using three different materials in the steady-state analysis where the air velocity is defined as 2 m/s. The materials used are only air (control), epoxy + h-BN additive filler material, and pure epoxy resin. The results obtained are given in Figures 6, 7, and 8.

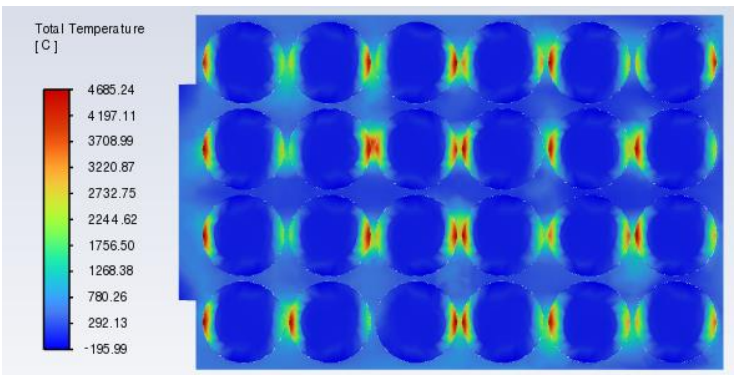

Figure 6. Temperature Distribution of the Analysis Using Air

In the analysis shown in Figure 6, where only air is used, it is observed that sufficient heat transfer does not occur around the battery cells. As a result, the maximum temperature reaches a physically unrealistic level of 4685 °C. This result shows that air is an insufficient cooling medium due to its low thermal conductivity.

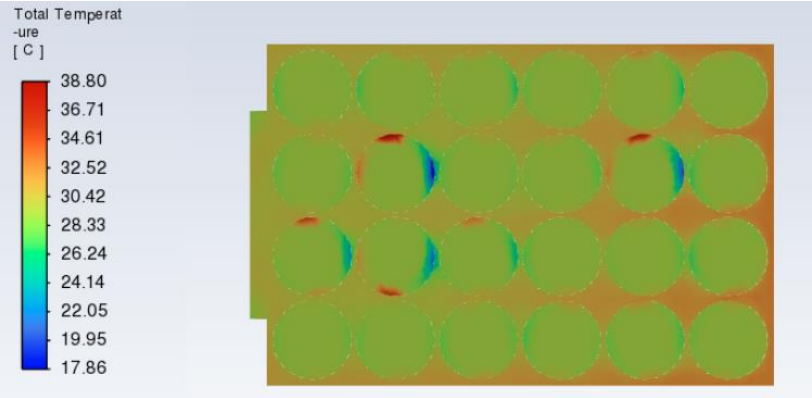

Figure 7. Temperature Distribution Obtained with Epoxy + H-BN Additive Filler Material

Figure 7 shows the analysis result performed with epoxy + h-BN additive filler material. Here, the maximum temperature value has been measured as 38.80 °C. The h-BN additive with high thermal conductivity ensured that the heat has been transferred more effectively from the battery surface to the outside; thus, a more homogeneous and controlled temperature distribution has been obtained.

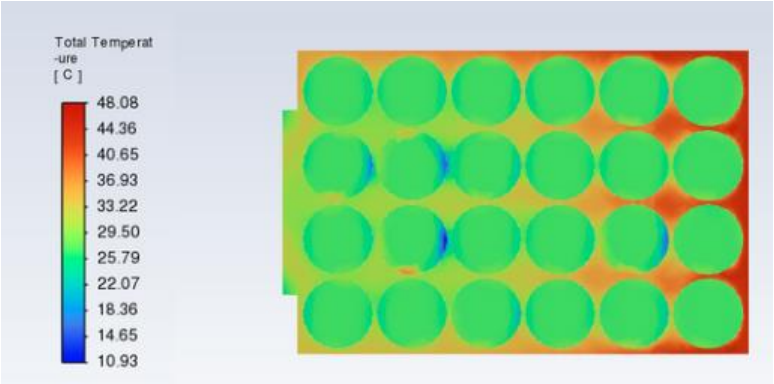

Figure 8. Temperature Distribution of the Analysis Using Pure Epoxy Resin

Figure 8 shows the result obtained with pure epoxy resin. In this case, the maximum temperature value has been calculated as 48.06°C. A higher temperature occurred compared to the epoxy + h-BN analysis, which showed that pure epoxy was insufficient to remove heat from the environment due to its low thermal conductivity. When these three analyses are compared, it is seen that epoxy + h-BN additive is the most efficient solution in terms of thermal management—using air directly as a filler material produces both inefficient and physically unsafe results.

Comparison Of Material Performances at Various Air Velocities

This section investigated the thermal performances of two different filling materials, epoxy + h-BN composite and pure epoxy resin structures, used at 3 m/s and 4 m/s air inlet velocities. In both analyses, the temperature distributions around the battery cells have been comparatively evaluated under constant ambient temperature, constant inlet velocity, and the SST k-w turbulence model. The temperature distributions obtained from the analyses using 3 m/s air velocity are given in Figure 9.

According to Figure 9, the maximum temperature value obtained in the analysis performed with epoxy + h-BN added material is 35.08°C, and the temperature difference between the cells is relatively low. This shows that the high thermal conductivity of h-BN allows the heat in the system to spread faster, and a more homogeneous temperature distribution is formed. When pure epoxy has been used at the same velocity, the maximum temperature value reached 45.76°C. In this case, where temperature gradients became apparent, it was observed that pure epoxy with low

thermal conductivity could not carry the heat out sufficiently and caused temperature accumulation around the cell. The temperature distributions obtained from the analyses using 4 m/s air velocity are given in Figure 10.

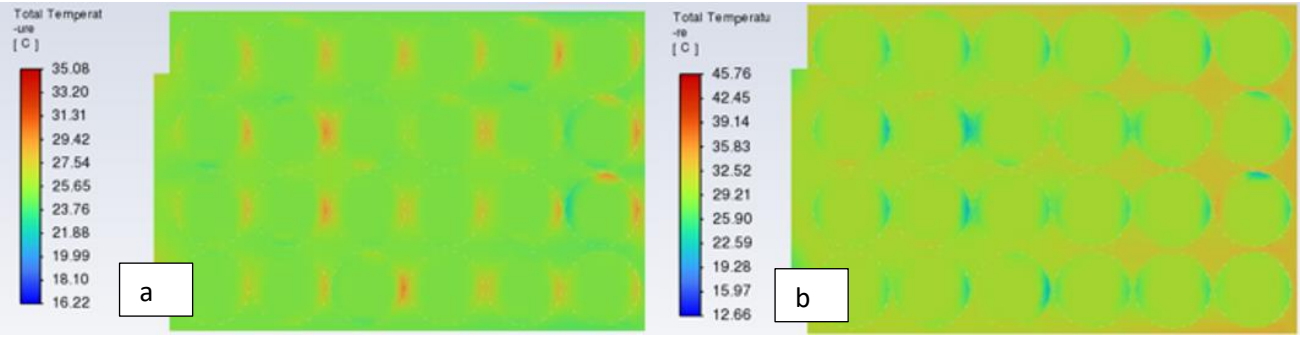

Figure 9. a. Epoxy + h-BN, **b.** Pure Epoxy

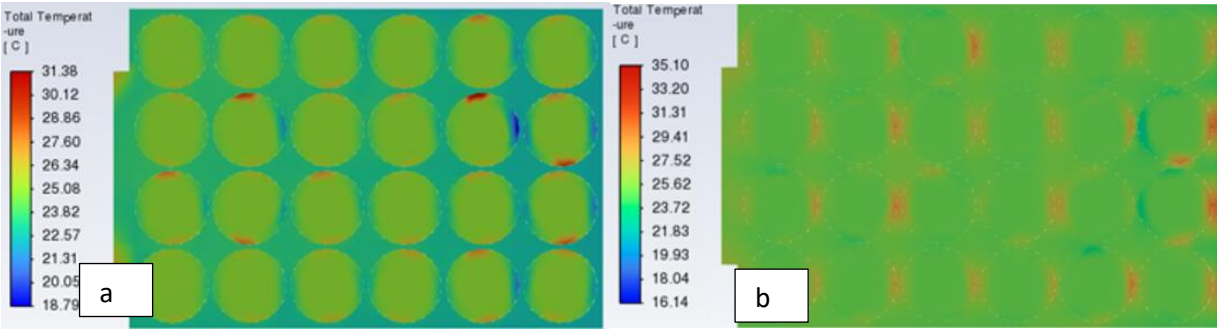

Figure 10. a. Epoxy + h-BN, **b.** Pure Epoxy

According to Figure 10, the maximum temperature obtained with the epoxy + h-BN additive material decreased to 31.38°C. The increased air velocity, combined with the high thermal conductivity of the filler material, provided a more efficient heat transfer. This indicates that a balanced cooling performance has been achieved between the cells. In the analysis performed with pure epoxy at a velocity of 4 m/s, the maximum temperature has been measured as 35.10°C. Although this value is lower than the previous 3 m/s condition, it is still higher than the epoxy + h-BN configuration.

In general, in the analyses where both velocities have been used, the epoxy + h-BN additive structure provided lower maximum temperature values than pure epoxy, and more homogeneous temperature distributions have been obtained due to these calculations. This reveals the effect of increasing the air velocity and the thermal properties of the filler material used in the battery thermal management.

Comparison Of Maximum Outlet Temperatures Obtained at Different Air Velocities

As seen in Figure 11, the outlet temperature tends to decrease depending on the air velocity in both filler material types. At all air velocities, the outlet temperatures in models using h-BN-added epoxy have been lower than those in pure epoxy. At 2 m/s air velocity, the outlet temperature has been measured as 38.8°C in the h-BN added epoxy model and 48.08°C in the pure epoxy model. At 3 m/s, these values have been 35.08°C and 45.76°C, respectively, and at 4 m/s, they were 31.38C and 35.11°C. The main reason for this difference is that the thermal conductivity of the h-BN-added epoxy (3.5 W/m K) is approximately 135 times higher than that of pure epoxy (0.0257 W/m K). The results show that the h-BN additive provides a more effective cooling performance in the battery system by removing heat more efficiently and offers a significant advantage, especially in low-velocity air flows.

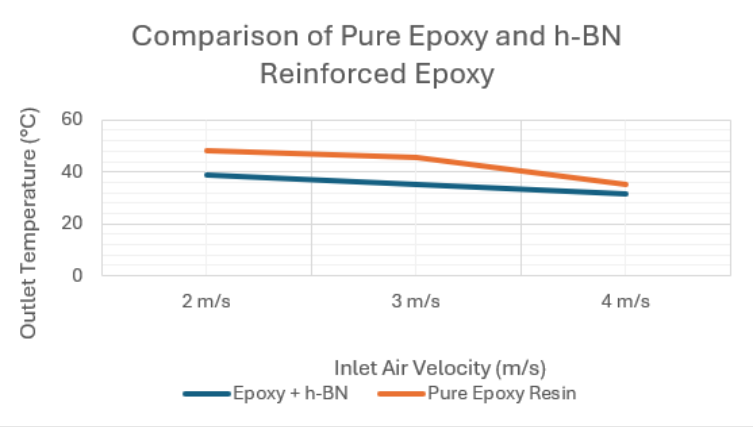

Figure 11. Comparison of Outlet Temperatures (°C) of Pure Epoxy and H-BN Reinforced Epoxy Filler Materials at Different Inlet Air Velocities

RESULTS

The thermal performances of pure epoxy and h-BN-filled epoxy used in the lithium-ion battery module were numerically investigated at inlet air velocities of 2, 3, and 4 m/s. In all operating conditions, the h-BN-filled epoxy exhibited lower maximum temperatures and a more uniform temperature distribution than pure epoxy. At an inlet air velocity of 2 m/s, the maximum battery temperature decreased from 48.08°C for pure epoxy to 38.80°C for the h-BN-filled epoxy. Similarly, the maximum temperatures obtained with the h-BN-filled epoxy were 35.08°C and 31.38 °C at inlet air velocities of 3 m/s and 4 m/s, whereas the corresponding values for pure epoxy were 45.76°C and 35.10°C, respectively. These results demonstrate that increasing the airflow velocity enhances the cooling performance of both filler materials, while the superior thermal conductivity of h-BN further improves heat dissipation and temperature uniformity throughout the battery module.

The observed thermal behavior is also consistent with the experimental and numerical findings reported by Mohonta et al. [25], who investigated polymer–BN composite thermal interface materials for 18650 lithium-ion battery modules. Their results showed that increasing the BN content in the thermal interface material effectively reduced the battery temperature under various discharge rates. A similar trend was obtained in the present study, where the incorporation of h-BN into the epoxy matrix significantly enhanced heat transfer and reduced the maximum battery temperature by approximately 19.3% at an inlet air velocity of 2 m/s compared with pure epoxy. This agreement with the published literature further supports the effectiveness of h-BN as a thermally conductive filler material for lithium-ion battery thermal management applications.

Overall, the results indicate that the combined use of h-BN-filled epoxy and forced-air cooling provides an effective thermal management strategy for lithium-ion battery modules. Future studies may further improve the proposed design by investigating different thermally conductive fillers, cooling techniques, and flow channel geometries.

Artificial Intelligence Contribution Statement

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

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