

Article

CFD-Taguchi-Based Geometric Optimization of a Liquid Cooled Battery Thermal Management System

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Abstract

In this study, a liquid-cooled Battery Thermal Management System (BTMS) incorporating aluminum heat-conducting blocks was numerically investigated to enhance the thermal performance of lithium-ion battery modules used in electric vehicles. The proposed system was designed for a battery module consisting of cylindrical lithium-ion cells, and the effects of different geometric configurations on thermal behavior were analyzed using the Computational Fluid Dynamics (CFD) method. To efficiently evaluate the multi-parameter design space with reduced computational cost, a Taguchi L9 orthogonal experimental design was employed. The cooling channel configuration, aluminum heat-conducting block height, and battery pack geometry were considered as the primary design variables. The performance of each design configuration was assessed based on maximum temperature ($T_{\max}$) and temperature uniformity (ΔT). Furthermore, an Analysis of Variance (ANOVA) was conducted to quantify the influence of the design parameters on the thermal performance of the system. The results revealed that the configuration comprising eight cooling channels, a 65 mm aluminum block height, and a 1 + 8 cylindrical battery arrangement exhibited the best thermal performance, achieving a maximum temperature of 303.45 K and a temperature difference of 1.25 K. The optimal design configuration provided a more uniform temperature distribution within the battery module, thereby enhancing thermal safety and operational reliability. Overall, the integration of CFD and the Taguchi method offers a systematic and efficient optimization framework for BTMS design, enabling effective evaluation of design alternatives with a reduced number of simulations and shorter computational time.

Keywords: Battery Thermal Management System (BTMS); lithium-ion battery; Computational Fluid Dynamics (CFD); Taguchi method; thermal optimization

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1. Introduction

The continuous growth of the global population, rapid industrialization, and technological advancements have led to a substantial increase in worldwide energy demand. This growing energy consumption, largely driven by the extensive use of fossil fuels, has resulted in increased greenhouse gas emissions and various environmental challenges, particularly climate change. Consequently, the development of sustainable energy solutions, the reduction of carbon emissions, the widespread adoption of renewable energy technologies, and the promotion of energy-efficient and low-carbon transportation systems have become critical priorities for achieving sustainable development goals [1,2].

Considering the significant contribution of the transportation sector to global energy consumption and carbon emissions, the development of environmentally friendly transportation technologies plays a vital role in mitigating environmental impacts and supporting sustainable mobility [3].

In this context, the increasing adoption of electric vehicles (EVs) and hybrid electric vehicles (HEVs) has significantly accelerated the demand for advanced energy storage technologies. Among various energy storage systems, lithium-ion (Li-ion) batteries have emerged as the dominant technology for EV applications owing to their high energy density, low self-discharge rate, high cycle efficiency, and long service life [4,5]. Currently, Li-ion batteries are manufactured in several cell formats, including cylindrical, prismatic, and pouch cells. Among these configurations, cylindrical and prismatic cells are particularly preferred in automotive applications due to their superior mechanical robustness, operational reliability, and electrochemical performance [6].

The safety, efficiency, and lifespan of Li-ion batteries are highly dependent on their operating temperature. Excessive battery temperatures accelerate electrochemical reactions and degradation mechanisms, leading to capacity fading and a significant reduction in battery lifetime. Moreover, elevated temperatures may trigger thermal runaway, which can result in severe safety hazards such as fire and explosion [7–9]. In addition to the maximum temperature, temperature non-uniformity within a battery pack is another critical concern. Uneven temperature distributions cause cells to age at different rates, resulting in performance degradation and reduced overall system reliability. Therefore, maintaining the battery temperature within an optimal operating range while ensuring a uniform temperature distribution among cells constitutes one of the primary objectives of Battery Thermal Management Systems (BTMSs).

Previous studies have suggested that the maximum battery temperature should be maintained below approximately 40–45 °C, while the temperature difference among cells should remain below 5 °C to ensure safe and efficient operation [10–12]. To achieve these thermal requirements, various BTMS technologies have been developed, including air cooling, liquid cooling, heat pipes, plate heat exchangers, and phase change material (PCM) based systems [13–15]. Air-cooling systems offer advantages such as simple structure, low cost, and ease of implementation; however, their relatively low heat removal capability limits their effectiveness under high thermal loads [16]. PCM-based systems are effective in suppressing transient temperature rises due to their latent heat storage capacity, yet their inherently low thermal conductivity often necessitates additional heat transfer enhancement techniques during prolonged operation [17,18]. Although heat pipes and plate heat exchangers provide excellent heat transfer performance, they may introduce additional complexity and cost. In contrast, liquid-cooling systems are widely regarded as one of the most effective thermal management solutions due to their superior heat removal capability and high heat transfer efficiency, enabling significant reductions in both maximum battery temperature and temperature non-uniformity [19,20].

Numerous experimental and numerical studies have been conducted to improve the performance of liquid cooled BTMSs. In particular, Computational Fluid Dynamics (CFD) has become a powerful tool for investigating the effects of channel geometry, flow conditions, and coolant properties on thermal performance. Hasan et al. [10] examined the influence of Reynolds number and nanoparticle size on the thermal performance of nanofluid-based liquid-cooling systems and reported that higher Reynolds numbers significantly enhance heat dissipation. Yang et al. [11] designed an innovative liquid-cooled plate with multi-branch channels for blade-type batteries and investigated its thermal performance using CFD methods. The study, which demonstrated that the combination of 3 distribution channels, a channel width of 3 mm, and an inlet velocity of 0.10 m/s provided the best performance, revealed that optimizing channel geometry in liquid-cooled battery

thermal management systems is a critical design parameter for both improving thermal performance and reducing energy consumption [11]. Dai et al. [16] developed a novel BTMS incorporating leaf-vein-inspired flow channels and investigated the effects of channel geometry and flow parameters on maximum battery temperature. Similarly, Simanjuntak et al. [21] proposed an interconnected straight-channel cooling plate design that enhanced flow mixing and achieved notable improvements in temperature uniformity. Furthermore, studies involving hybrid nanofluids have demonstrated considerable enhancement in heat transfer performance, although such improvements are often accompanied by increased pressure losses [22].

In recent years, researchers have focused not only on improving cooling performance but also on optimizing BTMS designs. Accordingly, the effects of various design parameters including channel number, channel width, channel height, flow direction, coolant flow rate, and inlet/outlet configurations on battery temperature and temperature distribution have been extensively investigated [23–26]. However, most existing studies primarily examine the individual effects of specific design variables, while the combined influence and relative importance of multiple geometric parameters remain insufficiently explored.

For multi-parameter engineering problems, the Taguchi design methodology has emerged as an efficient optimization approach for evaluating the effects of design variables on system performance. By employing orthogonal arrays, the Taguchi method significantly reduces the number of required experiments or simulations while enabling a systematic assessment of the relative influence of design parameters. Furthermore, statistical tools such as signal-to-noise (S/N) ratio analysis and Analysis of Variance (ANOVA) facilitate the reliable identification of optimal design conditions and dominant factors affecting system performance [27]. Owing to these advantages, the Taguchi method has been widely adopted in CFD-based optimization studies.

Although numerous investigations have examined the effects of channel geometry, coolant properties, and flow conditions in liquid-cooled BTMSs, studies evaluating the combined influence of multiple geometric design parameters, such as cooling channel configuration, aluminum heat-conducting block height, and battery pack arrangement, remain limited. Moreover, systematic investigations integrating CFD simulations with statistical optimization techniques to evaluate the effects of these parameters on maximum temperature and temperature uniformity are still scarce.

Therefore, this study numerically investigates the thermal performance of a liquid-cooled BTMS using the CFD approach. Three key design parameters, namely the cooling channel configuration, aluminum heat conducting block height, and battery pack arrangement, were evaluated using a Taguchi L9 orthogonal array design. The thermal performance of each design configuration was assessed based on two critical criteria: maximum temperature ($T_{\max}$) and temperature uniformity (ΔT). In addition, ANOVA was performed to quantify the contribution of each design parameter to the overall thermal performance. A novel BTMS architecture incorporating full-contact aluminum heat conducting blocks and vertically oriented liquid cooling channels is proposed and optimized. The findings of this study are expected to contribute to the development of high-performance, thermally safe, and reliable battery thermal management systems for next-generation electric vehicle applications.

2. Materials and Methods

2.1. Physical Model

The Battery Thermal Management System (BTMS) shown in Figure 1 comprises nine cylindrical lithium-ion battery cells (18 mm in diameter and 65 mm in height) and a full-contact aluminum heat-conducting block incorporating eight vertically oriented liquid-cooling channels. The aluminum block serves as an effective thermal pathway between

the battery cells and the coolant due to its high thermal conductivity, thereby promoting enhanced heat dissipation and temperature uniformity throughout the battery module.

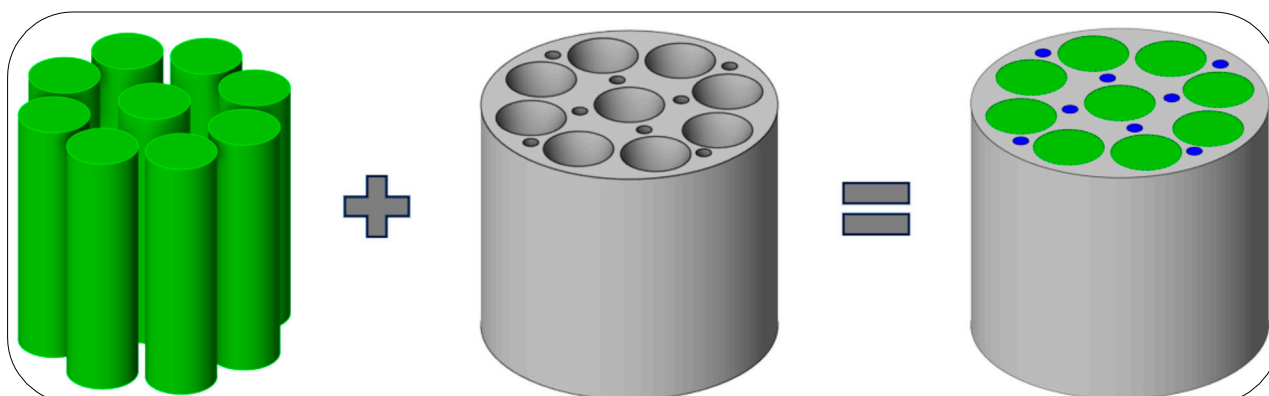


Figure 1. Three-dimensional geometry of the battery pack.

The proposed cooling structure features a novel and innovative design that ensures full contact thermal coupling with all battery cells, thereby enabling efficient heat transfer from the cells to the cooling body. As a result, the heat generated during battery operation is rapidly dissipated and effectively removed from the battery pack by the circulating coolant. The lithium-ion cells are arranged in a 1 + 8 configuration, consisting of a central cell surrounded by eight peripheral cells, forming a cylindrical battery pack architecture. The technical specifications of the lithium-ion battery cell used in this study are presented in Table 1. In the present BTMS, pure water was used as the working fluid. The thermophysical properties of the coolant and the other components of the BTMS are summarized in Table 2.

Table 1. Technical specifications of the battery cell [28].

Parameters	Value
Battery Type	Lithium Iron
Diameter	18 mm
Height	65 mm
Cell Voltage	3.3 V

Table 2. Thermophysical properties of the battery pack components [28].

Properties	Battery Cell	Aluminum	Pure Water
Density (kg/m ³)	1760	2719	998.2
Specific heat (J/kg·K)	1108	871	4128
Thermal conductivity (W/m·K)	3.91	202.4	0.600
Dynamic viscosity (Pa·s)	-	-	0.001003

2.2. Taguchi Optimization

The BTMS geometry was optimized using the Taguchi method, which enables the simultaneous evaluation of multiple design parameters. Three control factors block height (mm), battery arrangement, and cooling channel configuration were considered, each defined at three distinct levels. In all cases, the cooling channel diameter was kept constant at 4 mm. The design configurations and corresponding parameter levels used in the study are illustrated in Figure 2.

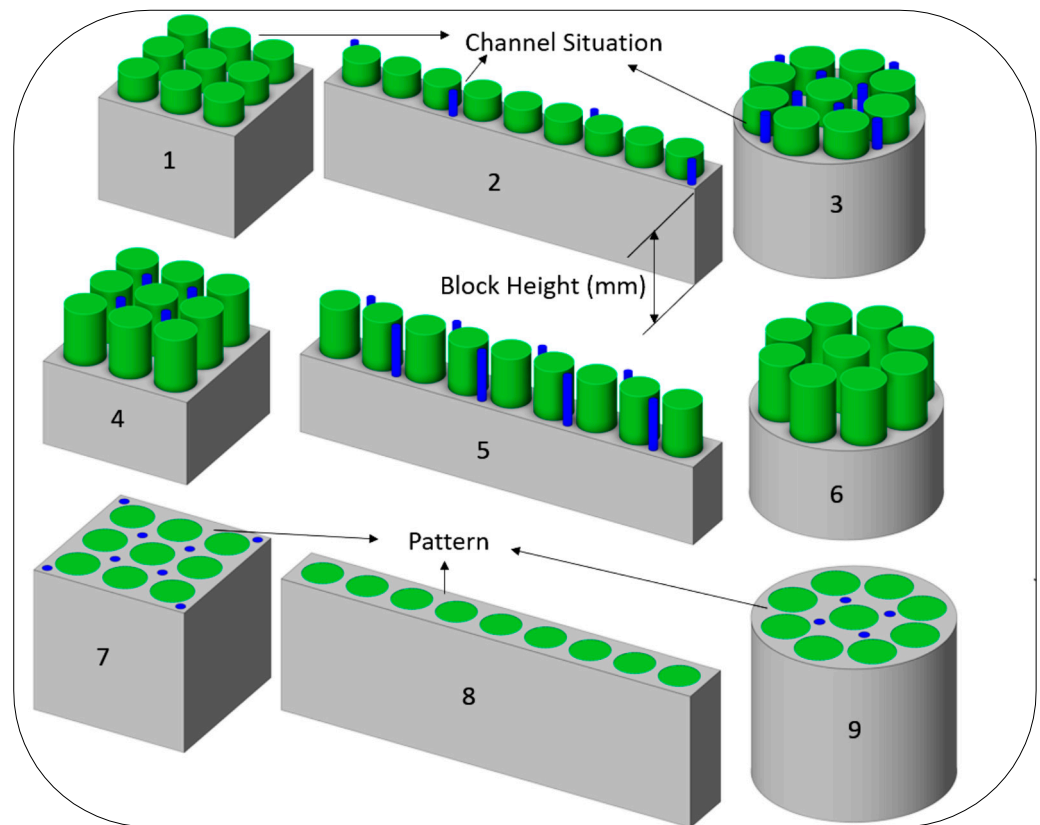


Figure 2. Representation of geometries and parameter configurations from experimental designs.

Using the factors and levels presented in Table 3, a total of nine experimental runs were generated based on the Taguchi L9 orthogonal array, as summarized in Table 4. Three-dimensional transient simulations were performed using ANSYS Fluent, 2024 R1 considering a 5C discharge rate over a simulation time of 720 s. For each case, the maximum battery temperature (T) and the temperature difference between cells (ΔT) were determined as the primary performance indicators of the battery pack.

Table 3. Factors and levels used in Taguchi optimization.

Factors	Levels		
	1	2	3
A. Height (Block Height)	40	52.5	65
B. Pattern (Cell Pattern)	3 × 3	1 × 9	1 + 8
C. Cooling (Channel Situation)	No	4	8

Based on the results obtained from nine CFD simulations, the signal-to-noise (S/N) ratios of the performance responses were calculated using the Taguchi “smaller-is-better” criterion, as expressed in Equation (1) [24]. Here, S/N denotes the signal-to-noise ratio (dB), y_i represents the performance value obtained from each experiment or simulation, and n is the number of repetitions.

$$\frac{S}{N} = -10 \log \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (1)$$

Table 4. Experimental design matrix based on the L9 (3³) orthogonal array.

Exp. No	A	B	C		Exp. No	Height (mm)	Pattern	Cooling
1	2	1	1		1	52.5	3 × 3	No
2	2	2	2		2	52.5	1 × 9	4
3	2	3	3		3	52.5	1 + 8	8
4	1	1	3		4	40	3 × 3	4
5	1	2	3		5	40	1 × 9	8
6	1	3	1		6	40	1 + 8	No
7	3	1	3		7	65	3 × 3	8
8	3	2	1		8	65	1 × 9	No
9	3	3	2		9	65	1 + 8	4

2.3. Governing Equations

The conservation equations of mass, momentum, and energy for the BTMS are presented as follows. The coolant flows through the liquid cooling channels as pure water. The fluid is assumed to be incompressible and Newtonian. Since the flow within the analyzed channel geometries corresponds to low Reynolds numbers ($Re < 2300$), the simulations were conducted under the assumption of laminar flow. The governing equations for mass, momentum, and energy conservation in the fluid domain are given in Equations (2), (3) and (4), respectively [29–31].

- Continuity equation:

$$\frac{\partial \rho_f}{\partial t} + \nabla \cdot (\rho_f \vec{v}_f) = 0 \quad (2)$$

- Momentum conservation equation:

$$\frac{\partial}{\partial t} (\rho_f \cdot \vec{v}_f) + \nabla \cdot (\rho_f \cdot \vec{v}_f \cdot \vec{v}_f) = -\nabla P + \nabla (\mu_f \nabla \vec{v}_f) \quad (3)$$

- Energy conservation equation:

$$\frac{\partial}{\partial t} (\rho_f C_{p,f} T_f) + \nabla \cdot (\rho_f C_{p,f} \vec{v}_f T_f) = \nabla (k_f \nabla T_f) \quad (4)$$

Here, ρ_f denotes the density of the coolant fluid, while ∇ represents the divergence operator of a vector field. v_f is the velocity vector of the coolant fluid. The static pressure, dynamic viscosity, specific heat capacity, temperature, and thermal conductivity of the coolant are denoted by P , μ_f , $C_{p,f}$, T_f , and k_f respectively. The energy conservation equations for the battery cells and the cooling channels are formulated in Equations (5) and (6), respectively [23].

$$\rho_b C_{p,b} \frac{\partial T_b}{\partial t} = \nabla (k_b \nabla T_b) + \dot{q}_g \quad (5)$$

$$\rho_c C_{p,c} \frac{\partial T_c}{\partial t} = \nabla (k_c \nabla T_c) \quad (6)$$

Here, ρ_b denotes the density of the battery cell, $C_{p,b}$ the specific heat capacity, T_b the temperature, k_b the thermal conductivity, and $\dot{q}_g$ the volumetric heat generation rate. Similarly, ρ_c represents the density of the cooling channel, $C_{p,c}$ the specific heat capacity, T_c the temperature, and k_c the thermal conductivity. In all simulations, the thermophysical properties of the fluids and the heat generation rate of the battery cells were assumed to remain constant throughout the analysis.

2.4. Numerical Analysis

2.4.1. Initial and Boundary Conditions

At the initial time ($t = 0$ s), the temperatures of the battery cells (T_b), channel surfaces (T_s), and coolant fluid (T_f) were assumed to be 300 K. A velocity inlet boundary condition was applied at the inlet surfaces, while a pressure outlet boundary condition was imposed at the outlet. All external surfaces were considered adiabatic walls. The inlet velocity of the coolant was kept constant at 0.1 m/s for all cases. In this study, the coolant inlet velocity was kept constant at 0.1 m/s. This value was selected because it is one of the most commonly used operating conditions in previous CFD studies on liquid-cooled battery thermal management systems. Thus, the effect of geometric design parameters on thermal performance could be directly compared under the same operating conditions. Furthermore, the Reynolds number calculated for this inlet velocity is approximately $Re = 398$, and it has been confirmed that the flow occurs in the laminar regime in all analyses [6,11,23].

2.4.2. Validation of the Battery Heat Generation Model

Prior to the CFD analyses, the heat generation model was validated using data from a selected reference study in the literature [28]. A single battery cell was simulated under a 5C discharge rate over a period of 720 s. As shown in Figure 3, a very good agreement was observed between the maximum temperature values obtained from the present CFD model and those reported in the reference study, with an error of only 0.01%. This confirms the accuracy and reliability of the heat generation model employed in this study.

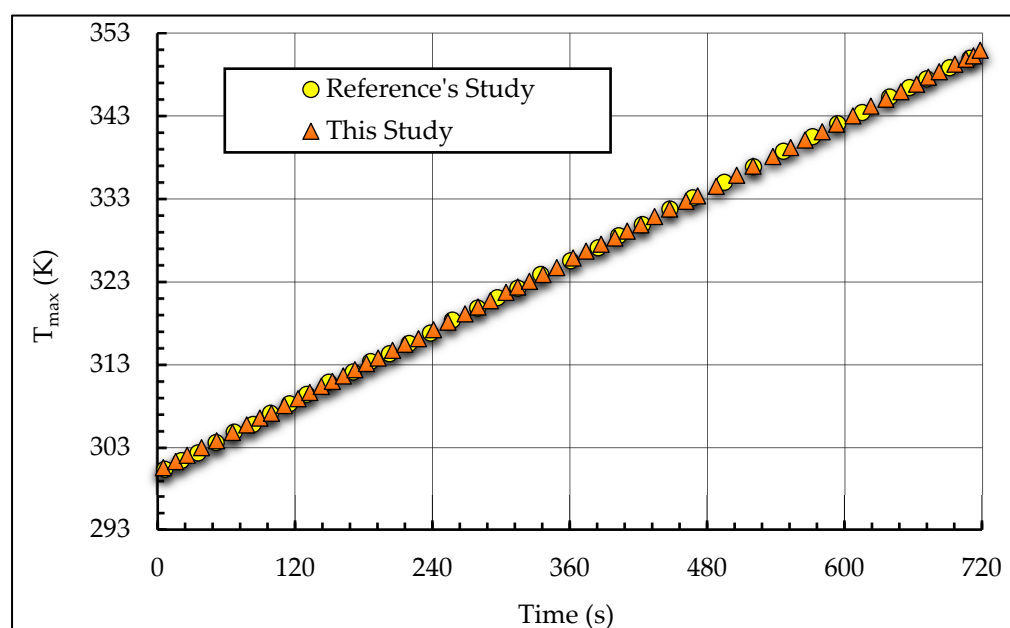


Figure 3. Validation results of the single battery heat generation model.

2.4.3. Mesh Independence Study

To avoid unnecessary computational cost and to ensure the reliability of the numerical results, a mesh independence study was conducted for Case 1 by progressively refining the mesh into five different grid resolutions. The results are presented in Figure 4. For a transient simulation at a 5C discharge rate, the maximum temperature values were obtained as 390 K for 202,252 elements, 352 K for 400,128 elements, 336 K for 802,504 elements, 330.09 K for 1,678,661 elements, and 329.8 K for 3,320,138 elements. Since the difference between the last two consecutive mesh refinements was only 0.09%, the mesh con-

taining 1,678,661 elements was selected as the optimal mesh configuration. All computational meshes were generated using ANSYS Meshing 2024 R1 software. The mesh quality was ensured by maintaining a maximum skewness range of 0.79–0.83 and a minimum orthogonal quality range of 0.17–0.31, ensuring sufficient numerical accuracy and stability for all simulations.

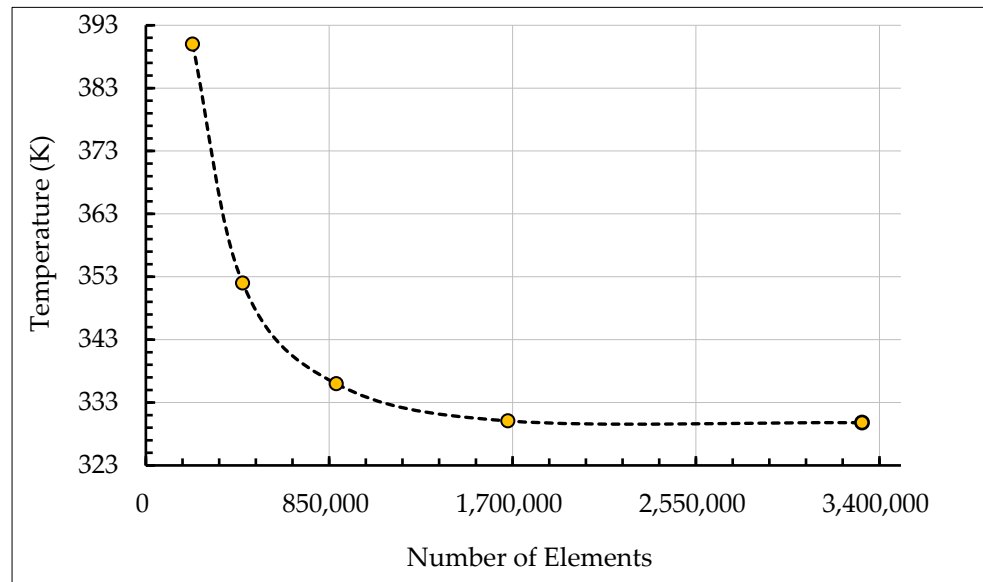


Figure 4. Mesh independence study for Case 1.

2.4.4. Time Step Independence Study

In transient numerical simulations, the time step size (Δt) is a critical parameter that directly influences solution stability and computational efficiency. To determine an appropriate time step size for the BTMS analysis, four different time step values were tested under a 5C discharge condition, and the resulting maximum temperature differences between battery cells are presented in Figure 5. No significant variation in temperature difference was observed between time steps of 0.5 s and 1.0 s. Therefore, a time step size of 1 s was selected as the optimal value for all transient simulations, ensuring both numerical accuracy and computational efficiency.

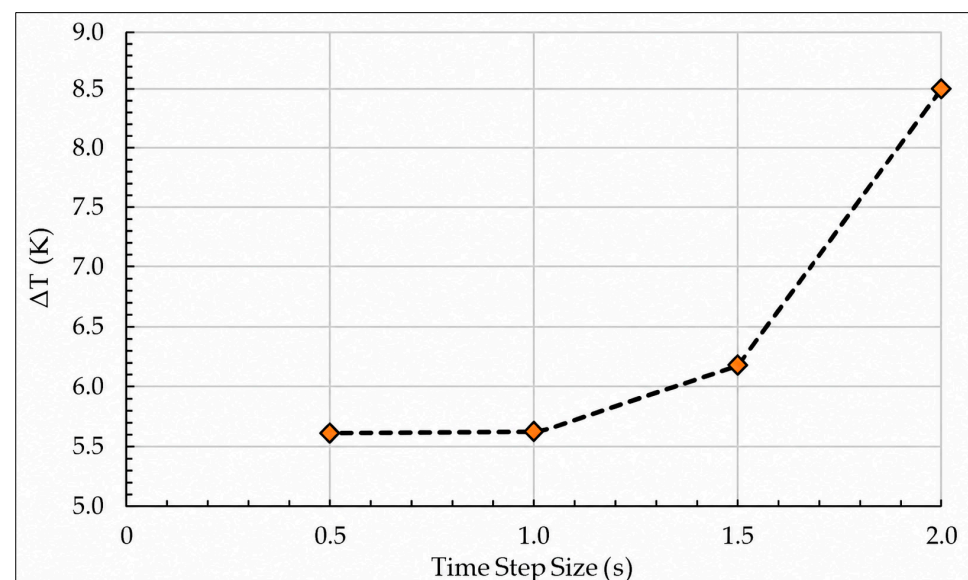


Figure 5. Time independence study for Case 1.

3. Results and Discussion

In this study, a Taguchi optimization approach was employed to evaluate the effects of block height and different battery arrangements with vertically integrated cooling channel configurations on the thermal performance of a lithium-ion battery pack.

3.1. CFD Analysis of the Taguchi Experimental Design

The nine experimental cases obtained from the Taguchi L9 orthogonal array were simulated using Ansys Fluent 2024 R1 in a transient three-dimensional framework under a 5C discharge condition. The results are summarized in Table 5. Factor A (Height, mm) represents the height of the full-contact aluminum block, which was selected due to its high thermal conductivity. Factor B (Pattern) corresponds to different battery arrangements. Accordingly, three configurations consisting of nine cells were considered: 3×3 (square arrangement), 1×9 (rectangular arrangement), and $1 + 8$ (cylindrical arrangement), in which one central cell is surrounded symmetrically by eight cells. Factor C (Cooling) represents the presence of vertical liquid cooling channels, with three levels defined as no channel, four channels, and eight channels. The output responses were selected as the maximum battery temperature ($T_{\max}$) and the temperature difference between cells (ΔT), which are key indicators of thermal performance. According to Table 5, thermal management requirements ($T_{\max} < 45\text{ }^{\circ}\text{C}$, $\Delta T < 5\text{ }^{\circ}\text{C}$) were satisfied in Experiments 2, 3, 7, and 9. Among all nine simulation cases, the best thermal performance was achieved in Experiment 7, which exhibited the most favorable combination of low maximum temperature and improved temperature uniformity.

Table 5. Simulation results of the experimental design based on the L9 (3^3) orthogonal array.

Exp. No	Height (mm)	Pattern	Cooling	$T_{\max}$ (K)	ΔT (K)
1	52.5	3×3	No	330.09	5.64
2	52.5	1×9	4	309.26	4.31
3	52.5	$1 + 8$	8	305.90	3.04
4	40	3×3	4	318.50	12.59
5	40	1×9	8	316.01	12.74
6	40	$1 + 8$	No	334.14	5.84
7 *	65	3×3	8	303.48	1.28
8	65	1×9	No	321.26	0.51
9	65	$1 + 8$	4	306.20	1.67

* means the most appropriate parameter for this analysis.

3.2. Signal-to-Noise (S/N) Ratio and ANOVA Analysis of the Taguchi Design

In order to evaluate the effectiveness of the parameter levels used in the Taguchi optimization, the signal-to-noise (S/N) ratio was calculated using Minitab Statistical Software (Version 22). The “smaller-is-better” criterion was applied with respect to the maximum temperature ($T_{\max}$) response to determine the S/N ratios. According to Figure 6, the optimal combination obtained from the Taguchi analysis corresponds to the A3B3C3 configuration, whose solid model is presented in Figure 7.

To evaluate the effects of the parameters used in the Taguchi optimization on thermal performance, an Analysis of Variance (ANOVA) was performed using the General Linear Model (GLM) approach. According to the results presented in Table 6, the cooling channel configuration (Cooling) exhibited the most significant influence on the response variable. The full contact aluminum block height (Height) was identified as the second most influential parameter, while the battery arrangement pattern showed the least effect on the overall thermal performance.

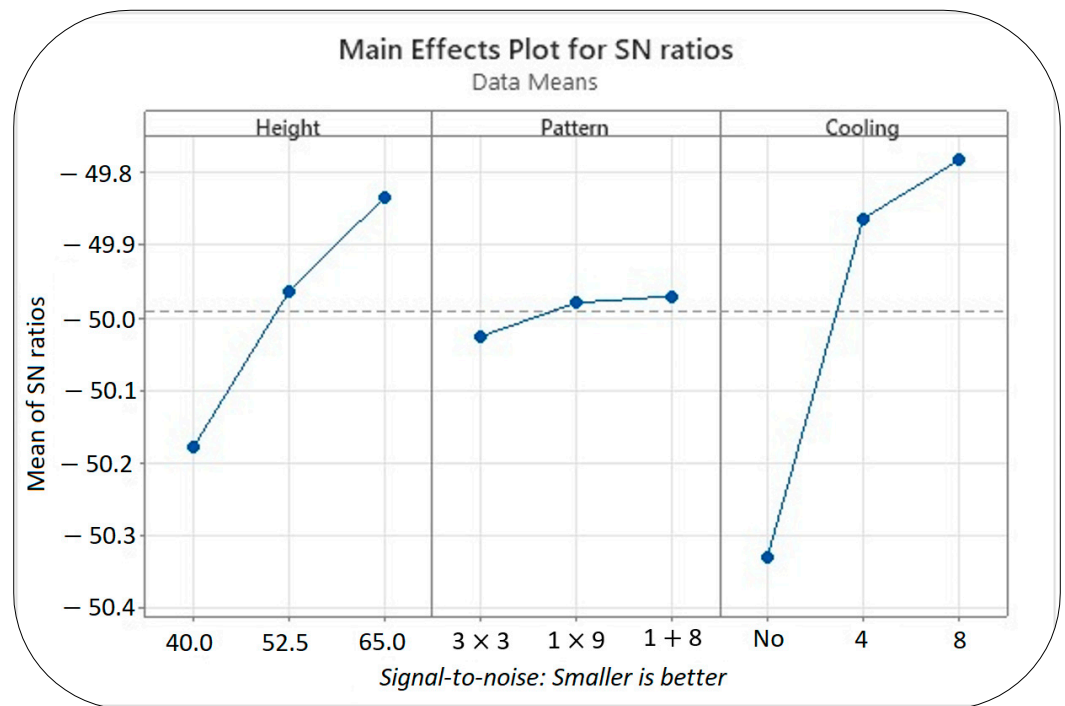


Figure 6. *S/N* ratio results of the experimental design based on the L9 (3^3) orthogonal array.

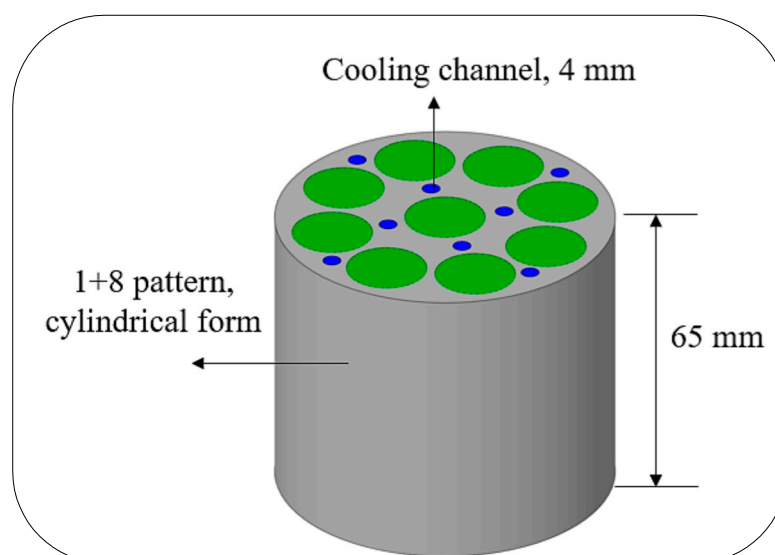


Figure 7. Solid model of the optimal configuration obtained from Taguchi optimization (A3B3C3).

Table 6. ANOVA results of the L9 (3^3) orthogonal array experimental design.

Source	DF	Adj SS	Adj MS	F-Value	p-Value
A. Height	2	241.598	120.799	29.01	0.033
B. Pattern	2	7.196	3.598	0.86	0.536
C. Cooling	2	704.533	352.266	84.60	0.012
Error	2	8.328	4.164		
Total	8	961.655			

3.3. Confirmation Analysis and Selection of the BTMS

To verify the reliability of the results obtained from the Taguchi analysis, a confirmation simulation (Confirmation Run) was performed using the optimal configuration geometry under a transient condition at a 5C discharge rate. First, a mesh independence study was conducted, and an optimized mesh structure was generated, ensuring a high-quality computational grid with a maximum skewness of 0.8 and a minimum orthogonal quality of 0.20. The mesh model and boundary conditions are presented in Figure 8. Due to the relatively low Reynolds number ($Re = 2300$), the flow was assumed to be laminar. A five-layer inflation (boundary layer) mesh was generated around the liquid cooling channels to accurately resolve near-wall effects. At the inlet, a velocity inlet boundary condition was applied with a constant flow velocity of 0.1 m/s. At the outlet, a pressure outlet boundary condition of 0 Pa was imposed. The heat generation within the battery cells was assumed to be constant and uniformly distributed in all directions throughout the simulation domain.

The CFD results obtained from the optimal configuration indicated a 2.34% improvement in thermal uniformity ($\Delta T = 1.25$ K) and a 0.01% reduction in maximum temperature ($T_{max} = 303.45$ K) compared to the best-performing case among the Taguchi experiments (Experiment 7). The comparison of ΔT values for all nine Taguchi cases is presented in Figure 9. It is observed that Experiment 8 exhibits the lowest temperature difference among all cases. This can be attributed to the 1×9 battery arrangement combined with a 65 mm full-contact aluminum block height. However, due to the absence of a liquid cooling channel in this configuration, the thermal performance does not reach an optimal level in terms of overall temperature management. As shown in Figure 10, the comparison of maximum temperature (T_{max}) values obtained from the nine Taguchi cases and the Taguchi-optimized configuration demonstrates that the proposed A3B3C3 design yields the best overall thermal performance. Therefore, it is selected as the final optimized BTMS design.

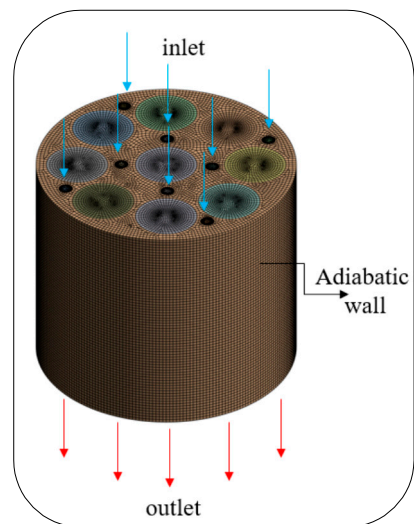


Figure 8. Mesh model and boundary conditions of the optimal configuration obtained from Taguchi optimization (A3B3C3).

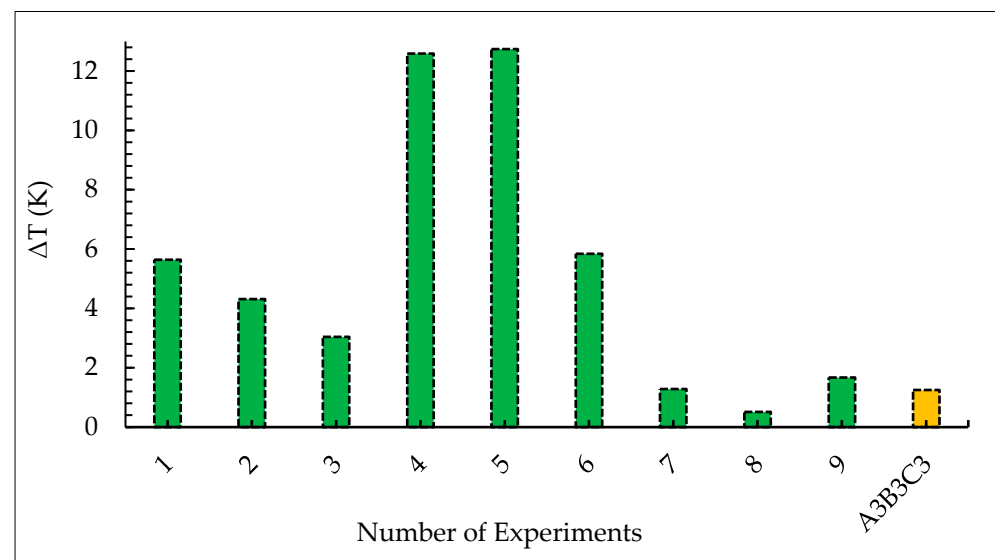


Figure 9. Comparison of inter-cell temperature difference (ΔT) between the optimal configuration (A3B3C3) and Taguchi experimental cases.

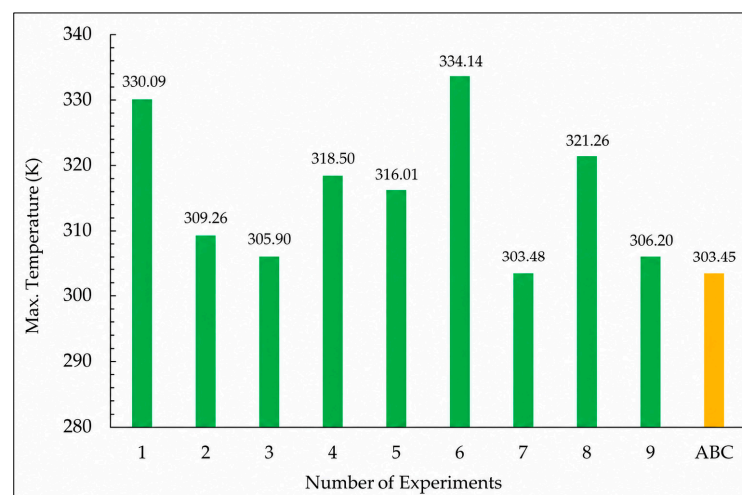


Figure 10. Comparison of maximum temperature ($T_{\max}$) between the optimal configuration (A3B3C3) and Taguchi experimental cases.

3.4. Taguchi Prediction Verification Test

According to the verification test presented in Table 7, the percentage deviation between the predicted response value and the CFD validation result was calculated as 0.48%. This corresponds to a prediction accuracy of 99.52%, demonstrating the high reliability of the Taguchi-based optimization model.

Table 7. Verification test results.

Response: $T_{\max}$ (K)				
		Prediction		CFD Value
Fit	SE Fit	95% CI	95% PI	
302.00	1.80	(294.30–309.70)	(290.30–313.70)	303.45
Deviation: 0.48%				
Accuracy: 99.52%				

4. Conclusions

The continuously increasing global population and the associated rise in carbon emissions pose a growing environmental challenge, making lithium-ion batteries used in environmentally friendly electric vehicles an increasingly important research focus. In this study, a numerical investigation was conducted to evaluate the simultaneous effects of three different geometric parameters on the thermal performance of a battery thermal management system (BTMS). A total of nine 18,650 lithium-ion battery cells were arranged in different configurations with vertically integrated liquid cooling channels. Using the Taguchi method, which enables multi-parameter optimization, nine experimental designs were generated, and three-dimensional CFD simulations were performed under a 5C discharge condition. The optimal configuration was identified using the signal-to-noise (S/N) ratio approach, and a confirmation simulation was carried out to verify the results, demonstrating the highest thermal performance.

The best-performing configuration consisted of a full-contact aluminum heat-conducting block with a height of 65 mm, integrated with eight vertical liquid cooling channels of 4 mm diameter, and a 1 + 8 cylindrical battery arrangement. This optimal design achieved a maximum temperature of 303.45 K and a temperature difference of 1.25 K. Among the investigated parameters, the cooling channel configuration exhibited the most significant influence on thermal performance, followed by the block height, while the battery arrangement had the least effect. This is likely due to the relatively small number of battery cells (nine cells) considered in the present study. This study was conducted solely under a 5C discharge condition and a constant coolant inlet velocity of 0.1 m/s, and focused on the effect of geometric parameters on thermal performance. Therefore, analyses of pressure loss, pumping power, performance at different charge/discharge ratios, as well as cost and weight analyses, were excluded from the scope of this study. Future studies aim to evaluate the thermo-hydraulic performance of the proposed design under equal total mass flow rate conditions, conduct analyses of pressure loss and pumping power, examine its performance at different C ratios, and comprehensively evaluate it in terms of manufacturability, cost, and weight.

Overall, this study presents a systematic, reproducible, and efficient design framework for high-performance and reliable battery thermal management systems in electric vehicles. The proposed approach is expected to contribute to the development of sustainable energy systems and support global zero-emission targets.

Author Contributions: Methodology, B.E. and G.T.; Validation, G.T.; Formal analysis, B.E. and G.T.; Investigation, B.E. and G.T.; Writing—original draft, B.E. and G.T.; Writing—review and editing, B.E. and G.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

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