



Research Paper

Battery heating strategy to enhance fast-charge performance at low temperatures

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ABSTRACT

Fast-charge of lithium-ion batteries (LiBs) in battery-powered electric vehicles (BEVs) can be completed within 15 min at 20 °C. However, at subzero temperatures the in-vehicle battery management system (BMS) limits charging speed to ensure battery safety, leading to prolonged charging times and long queues at charging stations. Active battery heating strategies are necessary to overcome this limitation, requiring more heat than conventional systems with a target range of 0–5 °C designed to prevent Li-plating. While improving coolant channel design is important, efficient heat utilization within integrated EV thermal management systems (TMS) is increasing attention. This study assessed heating demands for reducing fast-charge times and the influence of heating capacity on charging performance, including charging times, costs, and battery cell temperatures. An equivalent circuit model and a thermal model of a PTC heater-based battery thermal management systems (BTMS) were developed to simulate heating load scenarios, heating during fast-charge and single-heating. The results showed that heating during fast-charge, even without preheating, significantly reduced charging time. At –7 °C, it decreased from 3 h to 62 min, and at –20 °C with a larger heater capacity, it remained under 60 min, with additional heating costs remaining negligible at less than \$1. However, the impact of higher heater capacities on charging efficiency and temperature imbalances must be carefully evaluated. This study will contribute to the advancement of BTMS designs for enhancing fast-charge performance and provides a foundation for the development of integrated EV TMS for the cabin, powertrain, and battery.

1. Introduction

At temperature above or below the optimal range between 15 °C and 35 °C, lithium-ion batteries (LiBs) suffer from poor charging and discharging performance [1]. The battery-powered electric vehicles (BEVs) that use LiBs operate under a wide range of climatic conditions and are therefore strongly affected by temperatures. This degradation is pronounced at low temperatures especially subzero conditions [2], where it leads to shorter driving ranges, requiring more frequent charging of EVs. However, at low temperatures, the charging speed also decreases, resulting in longer charging times and causing long queues at charging stations. These limitations in battery performance and charging efficiency at low temperatures pose a significant challenge to the practicality and user convenience of BEVs, ultimately hindering their widespread adoption. While fast-charge known as DC charging can typically be completed within 15–20 min under optimal temperatures (SOC 0–80 %) [3], it can take about 3 h at –10 °C to charge even when

connected to a DC charger [4]. Some EV users recommend slow-charge known as AC charging at home as a practical alternative. However, due to the limited driving range at low temperatures, additional charging is often required along the way, even with a fully charged battery.

A critical issue at low temperatures is prolonged charging time, even with fast charging. This delay occurs because the battery management system (BMS) actively regulates charging speed to ensure battery safety and longevity, as battery performance degrades in cold conditions. In practice, fast-charge standards are established by organizations such as the International Electrotechnical Commission (IEC) and the Society of Automotive Engineers (SAE), based on external charging infrastructure specifications, including charger output power (≥ 50 kW), voltage levels (e.g., 400–1500 V), and connector standards (e.g., IEC 61851–23 for DC fast-charge, IEC 62196–3 for connectors, and SAE J1772 for AC/DC charging interfaces) [4–6]. However, the actual charging speed is regulated by the in-vehicle control system, the BMS, which adjusts charging based on battery conditions such as temperature and state of charge (SOC) [7].

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Nomenclature			
A	heat transfer area [m^2]	<i>CooltoAir</i>	from coolant to air
A_c	cross-sectional area of the coolant channel [m^2]	<i>CooltoCell</i>	from coolant to cell
c_p	specific heat [J/kgK]	<i>cover</i>	cover
C	capacitance [F]	<i>fin</i>	fin
<i>C-rate</i>	battery charge or discharge rate [C]	<i>gen</i>	heat generation
D_h	hydraulic diameter [m]	<i>heater</i>	PTC heater
F	Faraday constant [As/mol]	<i>initial</i>	initial
h	convective heat transfer coefficient [$\text{W/m}^2\text{K}$]	<i>irr</i>	irreversible heat generation
I	current [A]	<i>OC</i>	open circuit
k	thermal conductivity [W/mK]	p	polarization
L	characteristic length [m]	<i>ref</i>	reference
$\dot{m}$	mass flow rate [kg/s]	<i>rev</i>	reversible heat generation
n	number of transferred electrons	s	heat transfer area between the coolant and the cell
Nu	Nusselt number	<i>tpad</i>	thermal pad
Pr	Prandtl number	<i>wall</i>	wall
$\dot{Q}$	heat generation/transfer rate [W]	Acronyms	
Q_c	capacity of a fully charged battery [Ah]	<i>AC</i>	alternating current
R	internal resistance [Ω]	<i>ACB</i>	all-climate batteries
Re	Reynolds number	<i>AME</i>	absolute mean error
ΔS	entropy change [J/Kmol]	<i>BEV</i>	battery electric vehicle
T	temperature [$^\circ\text{C}$, K]	<i>BTMS</i>	battery temperature management systems
T	time [s]	<i>CC</i>	constant current
ΔT	temperature difference [$^\circ\text{C}$]	<i>coldFTP</i>	cold federal test procedure
U	voltage [V]	<i>CV</i>	constant voltage
UA	equivalent heat conductance [W/K]	<i>DC</i>	direct current
V	voltage [V]	<i>EV</i>	electric vehicle
V^*	volume [m^3]	<i>ICE</i>	internal combustion engine
Greek symbol		<i>LiB</i>	lithium-ion battery
η	efficiency	<i>max</i>	maximum
ρ	density [kg/m^3]	<i>min</i>	minimum
γ	aspect ratio of the coolant channel	<i>MSCC</i>	multistage constant current
x	characteristic distance [m]	<i>OCV</i>	open circuit voltage
Subscripts		<i>PCM</i>	phase change material
<i>air</i>	airside	<i>PI</i>	proportional-integral control
<i>al</i>	aluminum	<i>PTC</i>	positive temperature coefficient
<i>cell</i>	cell	<i>RMSE</i>	root mean square error
<i>cool</i>	coolant	<i>SOC</i>	state of charge
		<i>SHLB</i>	self-heating lithium-ion battery
		<i>TMS</i>	thermal management systems

Lithium plating (Li-plating), a phenomenon where lithium metal deposits on the anode surface, occurs under specific conditions: low temperatures [8], high charging C-rates, and high SOC [9]. This process can lead to dendrite formation, resulting in short circuits and thermal runaway [10]. To mitigate these risks, the BMS restricts charging speed by reducing the charging C-rate when the battery temperature is too low or too high, or when the SOC is elevated [11,12]. Consequently, reducing charging time at low temperatures cannot be achieved by simply increasing voltage or current from external systems. Min et al. [13] studied about an adaptive fuzzy current control strategy reducing charging time by 14 % while maintaining battery safety. However, such advanced control strategies have not yet been widely implemented in commercial BMS, where safety constraints still limit charging speeds. Thus, active heating strategies to raise the temperature of battery are crucial for improving fast-charge performance at low temperatures.

Unlike conventional internal combustion engine (ICE) vehicles, BEVs generate minimal waste heat, which can be reused in cold weather. Consequently, battery heating methods are generally divided into two categories: internal and external heating [14]. Internal heating methods typically employ high-current pulses by rapidly cycling the battery between charging and discharging during the early phase of charging. This

involves rapidly cycling the battery between charging and discharging at high currents during the early phase of charging [15–17]. This cycling generates heat within the battery. This technique allows for a faster increase in temperature, enabling rapid charging under cold conditions. Zhao et al. [18] studied an internal heating approach during the initial constant current (CC) phase of CC–CV charging by applying high-rate current pulses, with charge rates ranging from 0.5 to 2C and discharge rates between 3 and 4C. Their experiment at -10°C reduced the charging time by 36 min (23.4 %). Similarly, Ruan et al. [19] reported that DC heating increased the battery temperature by 2.1°C within 103 s at -30°C . While internal heating methods offer a higher heating rate, it negatively affect the battery life. The repeated high-current cycling inherently induces additional stress on the battery, which is expected to accelerate degradation [20].

External heating methods are commonly used for practical applications of EVs. These methods utilize various heat transfer media, such as air [21], liquid [22], heat pipes [23], and phase-change materials (PCMs) [24,25]. Wang et al. [26] investigated a liquid immersing pre-heating system (IPS) for lithium-ion battery packs and shown that it can achieve a rate of temperature rise (RTR) of up to 4.18°C/min , reducing the preheating time to 11 min from -28°C to 25°C while maintaining a

maximum temperature difference within 4 °C. Jun et al. [27] proposed a heat pipe-assisted hybrid fin design for battery preheating, achieving a 13.6 °C increase in the minimum battery temperature and reducing the internal temperature difference by 8.1 °C compared to conventional plain fins. Numerous studies have explored different heat transfer methods, but most of them focus on preheating. Battery preheating is an effective approach that optimally conditions the battery before charging or discharging (driving), thereby improving its performance and extending its lifespan. However, many studies on preheating do not sufficiently address the impact of preheating on reducing charging time within actual charging protocols. While preheating is beneficial, it is difficult to apply at low SOC levels before charging. If preheating has not been performed in advance, the time required for preheating at the charging station may also contribute to the total charging duration. Therefore, practical research on heating during charging without preheating is required. Heating during fast-charge involves simultaneous charging and discharging of the battery, and the charging time can vary depending on heat supply capacity, power consumption, battery heat generation rate, and battery temperature.

There are few studies about temperature and analyzing the impact of battery heating on EV charging time. Lindgren and Lund [10] showed that at −10 °C, fast-charge time increased by 88 % compared to 20 °C, while implementing battery heating reduced charging time by 28 %. Dai and Long [28] developed a battery thermal management system (BTMS) using refrigerant direct cooling, effectively controlling battery temperature at −20 °C. The system achieved a total charging time of 1 h 30 min including preheating time, with battery temperatures maintained about 31.5 °C, ensuring a maximum temperature difference of 4.1 °C. In this study, the fast-charge current map from Dai and Long [28] was adapted to simulate the battery heating on charging time.

In addition, unlike the previously mentioned studies focusing on improving heat transfer rate by designing conduction and convection channels, this study takes a broader vehicle thermal management perspective, evaluating how the heat capacity supplied by the system influences fast-charge performance. To achieve this, a baseline BTMS system was established to simulate battery state variations under different heat supply capacities during fast-charge. The findings of this study will contribute to the development of next-generation battery heating technologies for fast-charge and integrated thermal

management systems for electric vehicles.

For the baseline BTMS configuration, a liquid-based system utilizing a PTC heater—widely adopted in commercial EVs [29]—was selected. A basic coolant circuit BTMS was configured as illustrated in Fig. 1. The left side of Fig. 1 represents the battery cooling mode. In summer, when battery temperature is high, the coolant absorbs heat from the battery via channels beneath the battery pack and then transfer this heat to the refrigerant cycle through a heat exchanger, battery HX, effectively cooling the coolant. In winter, when the outdoor temperature is mildly low or during high-speed driving, there may be situations where the battery needs to be cooled. In such cases, heat is dissipated through a heat exchange process, where the coolant transfers heat from the battery to the outdoor air via the radiator. In this study, a battery electrical model and a BTMS thermal model were developed to implement fast-charge with battery heating.

Various techniques have been proposed to reduce low-temperature charging time; however, these methods often result in increased energy consumption. From the perspective of EV owners, charging times and costs are critical factors. Therefore, the additional charging costs caused by thermal management must be considered during the EV design stage. Increasing the heater capacity can quickly raise the battery temperature, thereby shortening the charging time. However, as charging costs can increase with power usage, this study examines charging costs and their implications for practical applications.

Finally, an analysis of a single-heating before the initiation of charging was also included. While most studies have focused on preheating during driving before arriving at a fast-charge station, some have explored a strategy in which the battery is first heated to a certain temperature using power from the charger after connection, and then charging begins. Because this study aims to design a BTMS with a heating control strategy to reduce the fast-charge time in extremely low temperatures, this approach was also analyzed.

2. Simulation model

2.1. Battery equivalent circuit model

Owing to the intricate structure of LiBs, it is often challenging to create models that can accurately predict the electrochemical behavior

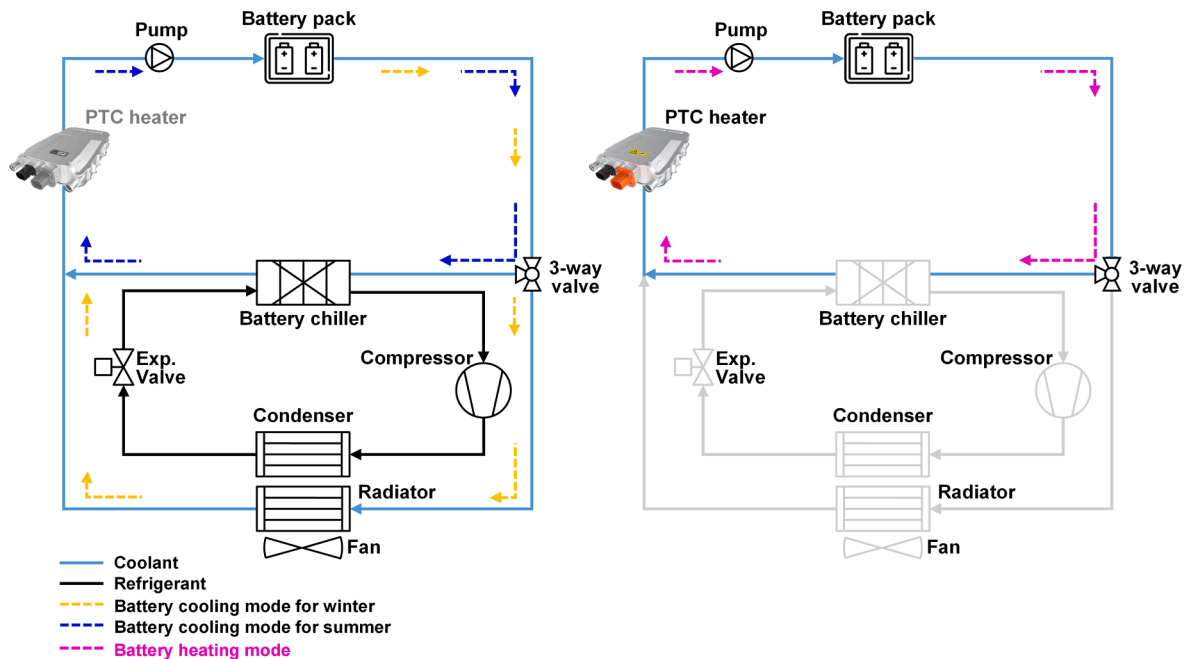


Fig. 1. Diagram of battery thermal management system (BTMS); cooling mode (left) and heating mode (right).

during charging. In several cases, the Thevenin equivalent circuit model [30] has been applied using the parameters obtained from the cell experiments. The electrical behavior of the Thevenin model can be described by the following equation:

$$\begin{cases} U = U_{OC} - U_p - IR \\ I = \frac{U_p}{R_p} + C_p U_p \end{cases} \quad (1)$$

In Eq. (1), U , U_{OC} , R , I , U_p , R_p , and C_p denote the terminal voltage, open circuit voltage (OCV), ohmic resistance, battery current, polarization voltage, polarization resistance, and polarization capacitance of the battery, respectively.

Typically, the battery current is negative during discharging and positive during charging, enabling calculating the SOC. SOC is expressed by Eq. (2).

$$SOC = SOC_{initial} + \int \frac{I}{Q_c} dt \quad (2)$$

$SOC_{initial}$ denotes the initial SOC of the battery, and Q_c represents the capacity of the fully charged battery. When a battery is heated during charging, the SOC changes in response to the net current, which comprises both the charging and discharging currents used for heating. Fast-charge typically involves high currents, allowing the battery to reach full charge within minutes, whereas the portion of the current used for heating remains comparatively minor. Because the vehicle remains stationary during charging, no current is consumed during propulsion. Therefore, under normal conditions of fast-charge with heating, the overall charging current remained predominantly positive.

This study modeled the battery pack using experimental cell data, including the OCV and resistances under varying temperatures and SOC conditions, from Zhang et al. [31]. They measured cell parameters over a temperature range from -20°C to 30°C and conducted experiments on the battery fast-charge process with positive temperature coefficient (PTC) coolant heating under low-temperature conditions [32].

2.2. Battery thermal model

The battery heat generation rate is expressed by the Bernardi equation, as shown in Eq. (3), in terms of reversible and irreversible heat generation. $\dot{Q}_{rev}$ represents the irreversible heat generation rate caused by the internal resistance R and current I ($U = U_{OC} - IR$). $\dot{Q}_{rev}$, the reversible heat generation rate, is expressed as a function of temperature T_{cell} and the experimentally measured entropy change ΔS . Similar to OCV, the battery heat generation rate is related to temperature and charge/discharge rates. At high C-rates, such as during fast-charge, $\dot{Q}_{rev}$ must be considered. The entropy change for the NMC-graphite LiB was obtained from Viswanathan et al. [33].

$$\dot{Q}_{gen} = \dot{Q}_{rev} + \dot{Q}_{irr} = I(U_{OC} - U) + IT_{cell} \frac{dU_{OC}}{dT_{cell}} = I^2 R - T_{cell} \Delta S \frac{I}{nF} \quad (3)$$

The battery pack comprised five modules, as shown in Fig. 2, with each module containing 60 cells, for the overall 300 cells connected in series and parallel. The inner cell heat transfer, driven by the heat generation rate and external heat transfer, was modeled by dividing each cell into a 2×3 grid of thermal nodes. For the surfaces of each module adjacent to the outermost edges, heat dissipation owing to natural convection along the x-, y-, and z-planes was also modeled. The thermal properties of the cells are listed in Table 1.

2.3. Liquid battery heating system model

The battery and coolant channels were modeled based on a real commercial EV system. As shown in Figs. 3 and 4, the coolant channels are positioned beneath the battery modules. In Fig. 3, the coolant heated by the PTC heater enters the battery pack and splits into three streams,

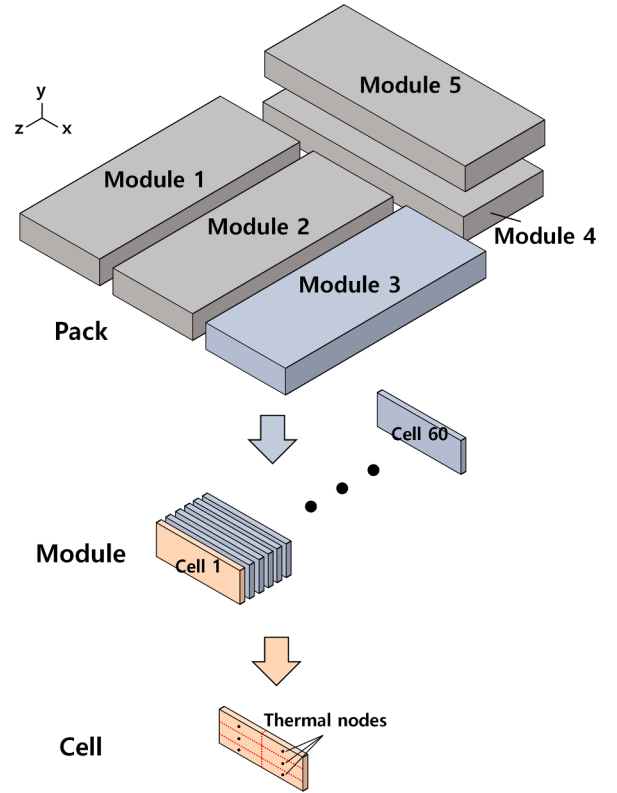


Fig. 2. Structure of the EV battery pack and thermal nodes of the cell.

Table 1

Thermal properties and specification of materials of the BTMS.

Material	ρ [kg/m ³]	c_p [J/kgK]	k [W/mK]	t [mm]
Aluminum fin	2700	893	170	0.5
Thermal pad	3100	930	3	2
Insulation case	2300	1430	1.5	4
Battery cell	1780	1000	60/0.8 (in/cross-plane)	15 (z-axis)
Wall	—	—	170	3
Cover	—	—	170	3

supplying Modules 1, 2, and 3. The coolant passing through Modules 1 and 3 is redirected to Modules 4 and 5, facilitating heat transfer to the cells. The coolant from Modules 1 and 3 merges with the coolant exiting Module 2 and flows out of the pack. The simplified figure is designed to aid in understanding the coolant path from a heat transfer modeling perspective. It represents the single-layer channel design, which is commonly used in EVs with NMC batteries. While the specific path may vary slightly depending on the vehicle, the heat transfer characteristics are generally similar, as they are based on the cell properties and structures like those shown in Fig. 4. Accordingly, the estimated heating demand in this study may differ for other battery type or double-layer channel designs.

Fig. 4 shows the x-axis cross-sectional view (along the coolant flow direction). The flow and insulation cases were positioned between the individual cells. Aluminum alloy fins are typically inserted between the cells to enhance heat dissipation [34]. The coolant transfers heat upward along the y-axis, whereas the thermal pad and fins facilitate heat conduction along the y- and x-axes, thereby increasing the cell temperature. A thermal pad (denoted by subscript *tpad*) was used to minimize the contact resistance between the cells. The heat transferred by the coolant to the cell along the y-axis ($\dot{Q}_{CooltoCell}$) was quantified using Eqs. (4)–(8).

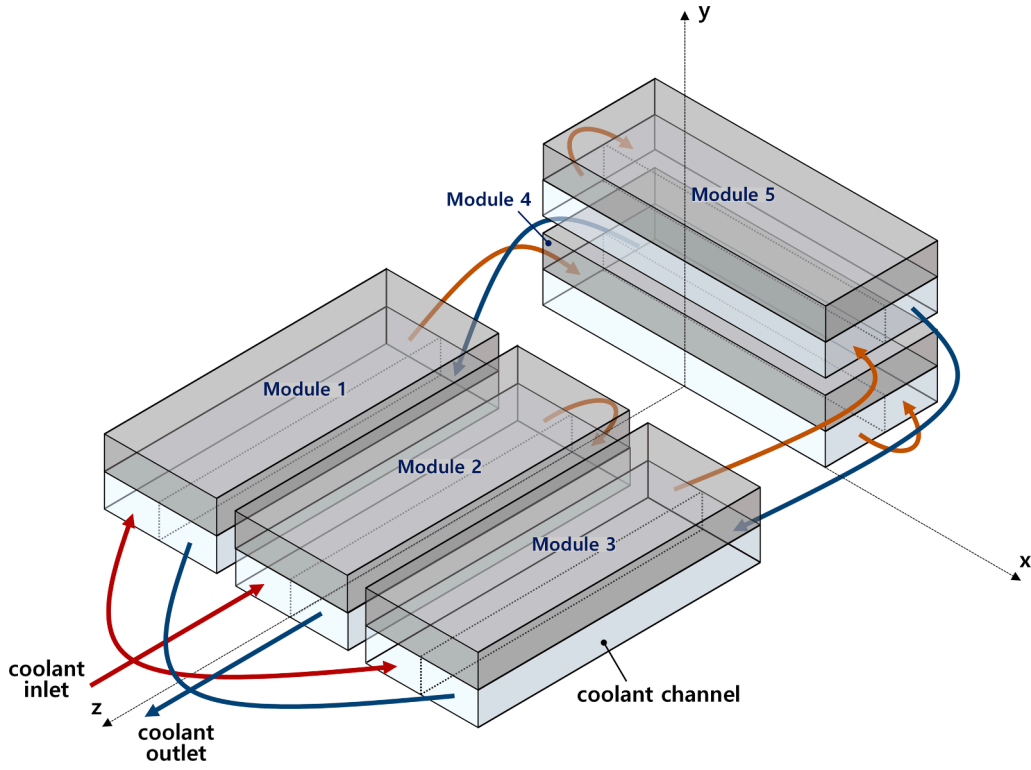


Fig. 3. Coolant channels and flow paths in the battery pack.

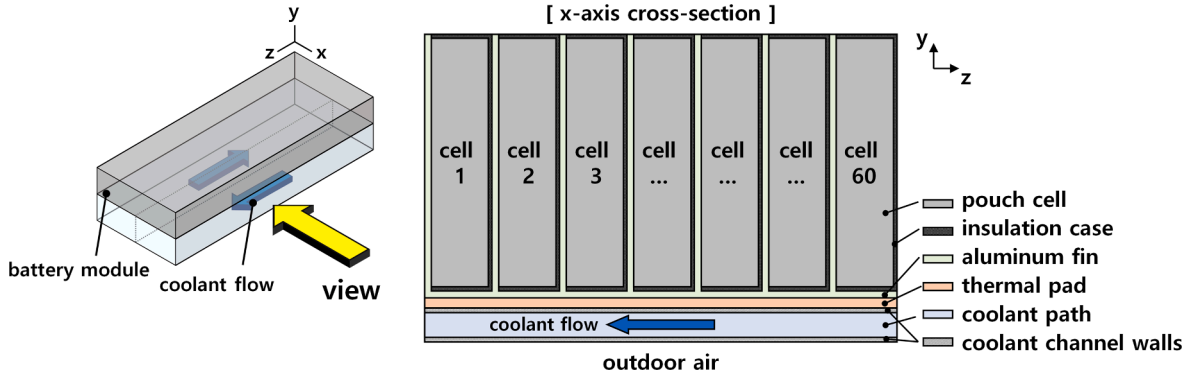


Fig. 4. Cross-sectional view of the battery pack with coolant flow.

$$\dot{Q}_{CooltoCell} = UA_{CooltoCell}(T_{cool} - T_{cell,node}) \quad (4)$$

$$UA_{CooltoCell} = \frac{1}{\frac{t_{fin}}{k_{al}A_s} + \frac{t_{wall}}{k_{wall}A_s} + \frac{t_{pad}}{k_{tpad}A_s} + \frac{1}{h_{cool}A_s}} \quad (5)$$

$$h_{cool} = \frac{Nu_{cool}k_{cool}}{D_{h,cool}} \quad (6)$$

$$Nu_{cool} = Nu_{ref} + 0.0499RePr\frac{D_{h,cool}}{L} \quad (7)$$

$$Nu_{ref} = 7.541(1 - 1.969\gamma + 5.664\gamma^2 - 12.87\gamma^3 + 19.35\gamma^4 - 16.20\gamma^5 + 5.510\gamma^6) \quad (8)$$

The overall heat transfer coefficient $UA_{CooltoCell}$ is obtained by integrating the coolant heat transfer coefficient h_{cool} within the thermal resistance circuit. A_s represents the heat transfer area between the coolant channels (denoted by the subscript *wall*) and the cells, thermal

pads, and fins. The thermal properties of each material are based on the values listed in Table 1. The Nusselt number of the coolant Nu_{cool} is calculated using Eqs. (7) and (8), as proposed by Kim et al. [35]. The coolant channel comprises 10 paths, and the reference Nusselt number Nu_{ref} for a microtube is expressed as a function of the coolant path aspect ratio γ , as shown in Eq. (8). $D_{h,cool}$ denote the hydraulic diameters of the coolant channels. Re and Pr represent the Reynolds and Prandtl numbers, respectively, which are fundamental dimensionless parameters that characterize flow and thermal properties.

Heat loss occurs from the coolant channels along the downward y-axis to the outdoor air through the cover, which is in contact with the environment. During charging, when the vehicle speed is 0 km/h, heat is transferred to the air via natural convection. The top surface of the battery pack is in contact with the vehicle body and is not exposed to ambient air as shown in Figs. 3 and 4. In the model, the top surface is assumed to be insulated. Using the thermal properties listed in Table 1, the equivalent heat conductance (UA) for this process was calculated using Eqs. (9)–(12). The heat transfer coefficient of air is calculated based on the average Nusselt number for laminar flow over a flat plate

Nu_{air} and the downstream distance x , corresponding to the boundary layer thickness.

$$\dot{Q}_{CooltoAir} = UA_{CooltoAir}(T_{cool} - T_{air}) \quad (9)$$

$$UA_{CooltoAir} = \frac{1}{\frac{1}{h_{cool}A_s} + \frac{t_{wall}}{k_{wall}A_s} + \frac{t_{cover}}{k_{cover}A_s} + \frac{1}{h_{air}A_s}} \quad (10)$$

$$h_{air} = \frac{Nu_{air}k_{air}}{x} \quad (11)$$

$$Nu_{air} = 0.664Re_x^{1/2}Pr^{1/3} \quad (12)$$

The energy conservation equation for the cell is given by Eq. (13). In this study, V_{cell}^* denotes the volume of the cell, and V_{cell} refers to its voltage. The one-dimensional energy conservation equation for the coolant channel is given by Eq. (14). A_c refers to the cross-sectional area of the coolant channel. Using the thermal model, the battery and coolant outlet temperatures for the next time step were predicted based on the boundary conditions, including the coolant inlet temperature and current battery temperature [36]. The rate of change of the coolant temperature over time within the channel $\frac{\partial T_{cool}}{\partial t}$ can be determined using the temperature gradient between the inlet and outlet of the coolant channel along the z -axis $\frac{\partial T_{cool,z}}{\partial z}$ in accordance with the boundary conditions.

$$\rho_{cell}c_{p,cell}\Delta V_{cell}^*\frac{\partial T_{cell}}{\partial t} = \Delta(UA)_x\frac{\partial T_{cell,x}}{\partial x} + \Delta(UA)_y\frac{\partial T_{cell,y}}{\partial y} + \Delta(UA)_z\frac{\partial T_{cell,z}}{\partial z} + \Delta\dot{Q}_{gen} \quad (13)$$

$$\rho_{cool}c_{p,cool}A_c\frac{\partial T_{cool}}{\partial t} = \dot{m}_{cool}c_{p,cool}\frac{\partial T_{cool,z}}{\partial z} + \frac{d\dot{Q}_{CooltoCell}}{dz} + \frac{d\dot{Q}_{CooltoAir}}{dz} \quad (14)$$

2.4. Validation results of the BTMS model

Test data from a commercial EV fast-charging event were used to validate the battery thermal model. The experiment involved fast-charge at -7°C with heating the battery using a 4 kW PTC heater. The BTMS configuration used in the test is the same as shown in Fig. 1. To analyze and utilize the fast-charge data collected from the vehicle via the CAN (Controller Area Network) system, CAN reverse engineering was employed for data acquisition. This approach provided access to key parameters, including the battery PTC ON/OFF status, maximum and minimum battery temperatures, cell voltage, battery current, battery pack coolant inlet temperature, and SOC. However, since the coolant flow rate data were not available from the vehicle, the design value was used for the simulation.

The model estimated the battery temperature based on boundary conditions, including the initial state and coolant flow rate in the channel. The comparison was conducted in terms of the SOC, battery temperature, coolant temperature, and cell voltage. The experimental and simulation conditions are listed in Table 2.

In the simulation, the initial states of the system and battery are identical to those used in the experiment. The PTC heater is controlled to turn off when the minimum battery temperature reaches 20°C . Fig. 5 (a)–(c) show the experimental and simulation results.

Table 2

Experimental and simulation conditions for fast-charge with battery heating.

Parameter	Values
Ambient air temperature ($^\circ\text{C}$)	-7
State of charge (SOC, %)	$7.5\text{--}70$
Battery type	NMC
Battery capacity (kWh)	77
Volumetric flow rate of coolant (L/min)	17
PTC heater capacity (kW)	4
Target battery temperature ($^\circ\text{C}$)	20

The root mean square error (RMSE) and absolute mean error (AME) for the battery SOC are 1.7 and 1.29, respectively, while for the minimum temperature, they are 0.99 and 0.84. For cell voltage, the RMSE and AME are 0.05 and 0.04, respectively, indicating reasonable error margins. A summary of the error values between experimental and simulation data is provided in Table 3.

Errors in coolant temperature arise from the absence of a pump flow rate model. In reality, the coolant flow rate is influenced by the pump RPM and temperature. Under initial low-temperature conditions and low RPM, increased coolant viscosity increases reduces the flow rate. However, in the simulation, the flow rate is fixed at the design value of 17 L/min. Consequently, during the initial phase, the experimental coolant temperature is higher than the simulated temperature. As the coolant temperature rises, viscosity decreases, increasing the flow rate and lowering the coolant temperature.

For battery temperature, the relatively low heat transfer coefficient of the battery results in good agreement between experimental and simulated temperatures during the initial phase. However, as the charging process progresses, differences in coolant temperature lead to an increased heat transfer rate, causing the simulated battery temperature to rise more than the experimental data. The minimum battery temperature begins to diverge after approximately 2000 s, with the simulated values exceeding the experimental results.

The difference in SOC primarily stems from variations in charging current (C-rate) influenced by battery temperature. In the initial phase, lower battery temperatures delay the increase in charging current, resulting in a lower SOC. As the battery temperature rises in the later phase, the charging current increases more rapidly, causing the simulated SOC to exceed the experimental SOC. Another contributing factor to the SOC error is the use of real vehicle data. To validate the battery thermal model, real vehicle data under fast-charging conditions were utilized. However, since the exact BMS-controlled charging current map from the test vehicle was unavailable, estimated charging currents were used based on battery temperature. As a result, average charging current values were applied in the 1000 s–2000 s and 2000 s–2500 s time intervals (Fig. 5(d)). These accumulated errors lead to a maximum SOC deviation of approximately 4 %p by the end of the simulation.

Based on this analysis, future studies should incorporate a pump coolant flow rate model to account for flow rate variations and enhance dynamic accuracy. Additionally, conducting module-level charging experiments would help expand the scope of model validation and improve overall reliability.

3. Fast-charge simulation with battery heating

The charging protocol used in this study was based on the multistage constant current (MSCC) protocol; its principles are illustrated in Fig. 6. The charging process consists of n stages of constant current (CC) [$I_1, I_2, I_3, \dots, I_n$] applied in series, where the current values typically decrease gradually as SOC increases ($I_1 > I_2 > I_3$). During each stage, the voltage increases with a constant current until it reaches a predefined threshold [$V_1, V_2, V_3, \dots, V_n$], at which point the process proceeds to the next stage with a lower current [37]. Within each stage, the charging current may vary according to the battery temperature (the charging current increases with temperature). Additionally, the SOC can control the end of each stage.

The MSCC protocol offers finer control than the general CC–CV protocol. By reducing the current at high SOC levels, the protocol helps prevent aging mechanisms, such as lithium plating, making it particularly suitable for EV charging systems [38]. This study adapted the fast-charge current map proposed by Dai and Long (2023) (as given in Table 4) for the simulation [28].

The simulation conditions are listed in Table 5. The initial battery temperature at the start of charging was assumed equal to the ambient temperature. The temperatures were set to 0°C , -7°C (following the cold FTP standard for winter energy efficiency testing), and -20°C to

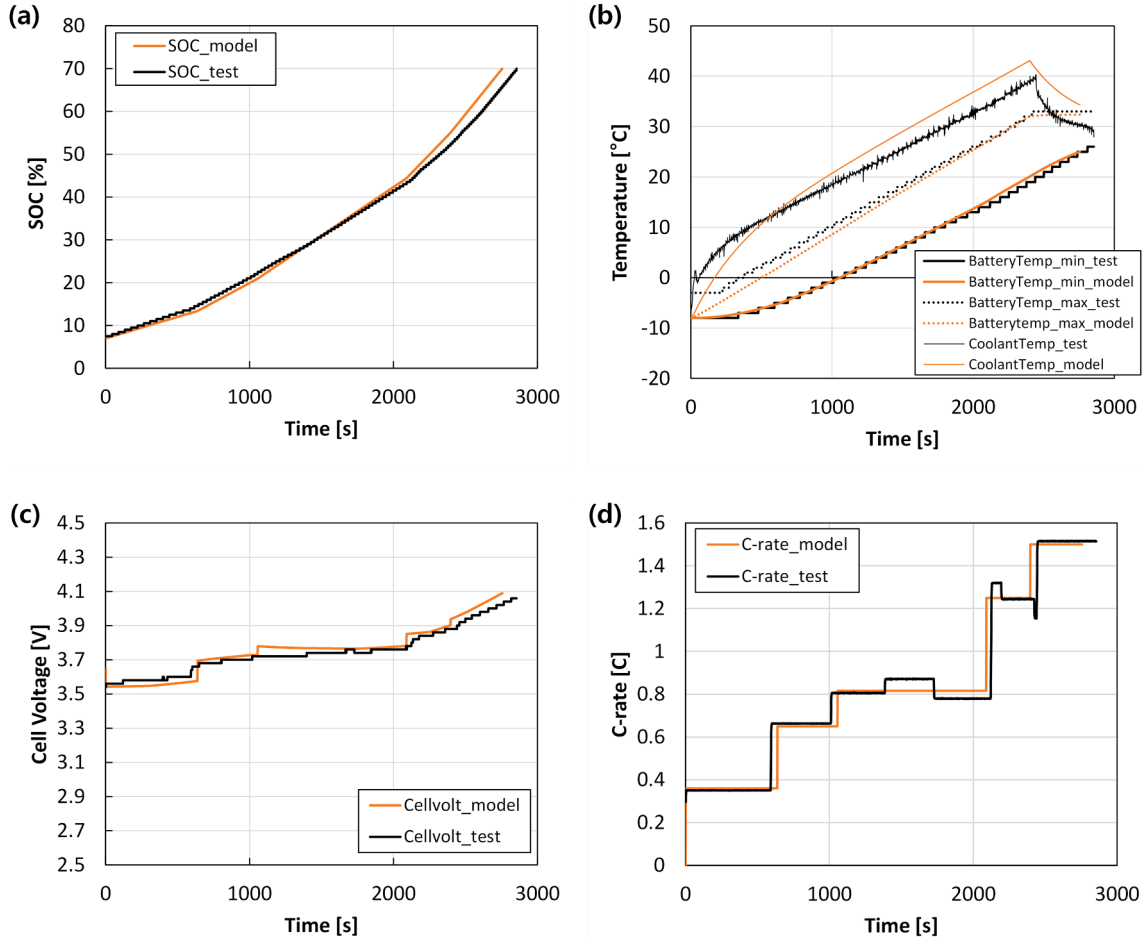


Fig. 5. Experimental and simulation results; (a) Battery SOC (b) Battery and coolant temperatures (c) Battery cell voltage (d) Charging C-rate.

Table 3

RMSE and MAE values between experimental and simulation data.

	$T_{bat,min}$	$T_{bat,max}$	T_{cool}	SOC	V_{cell}
RMSE	0.64°C	1.69°C	3.56°C	1.70 %p	0.04 V
MAE	0.48°C	1.39°C	3.26°C	1.29 %p	0.03 V

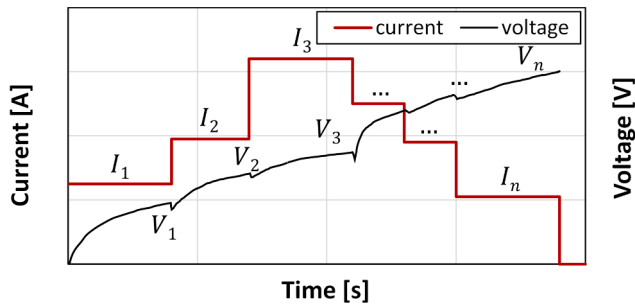


Fig. 6. Multistage constant current (MSCC) fast-charge protocol.

represent extremely low temperatures. To analyze the heating effect based on the design capacity of the battery heater, a heater with a maximum power of 15 kW was used, assuming an efficiency of 100 % ($\eta_{heater} = 1$).

The battery was heated during the fast-charge process, and the power of the PTC heater was regulated using a proportional-integral (PI) control algorithm. The PI control variables included the coolant temperature, ensuring that it did not exceed 80 °C. The end of the heating process is determined based on the charging map, which defines the charging speed according to the minimum battery temperature. Once the minimum battery temperature reached 20 °C, the heating process was terminated, as this allowed the charging speed to reach a maximum rate of 3C.

The simulation started with a battery SOC of 20 % and was stopped when the SOC reached 80 %, considering safety limitations [39].

3.1. Heating effects on fast-charge and battery performance at low temperatures

Fig. 7 illustrates the impact of heating on the charging performance and battery temperature during fast-charge. The dashed line represents the no-heating condition, and the solid line represents the heating condition. In the no-heating scenario, the total charging time was 6548 s (1 h, 50 min). As shown in the battery temperature graph, even without heating, the battery temperature increased owing to the internal heat generated by the charging currents and internal resistance. However, the increase is modest, with the temperature rising from 0 °C to 5.5 °C. According to the charging map, the charging rate between 0 °C and 15 °C is faster than slow charging but still remains at a relatively low level. In contrast, the heating scenario during charging increased the battery temperature from 0 °C to beyond 20 °C, increasing the C-rate. At

Table 4

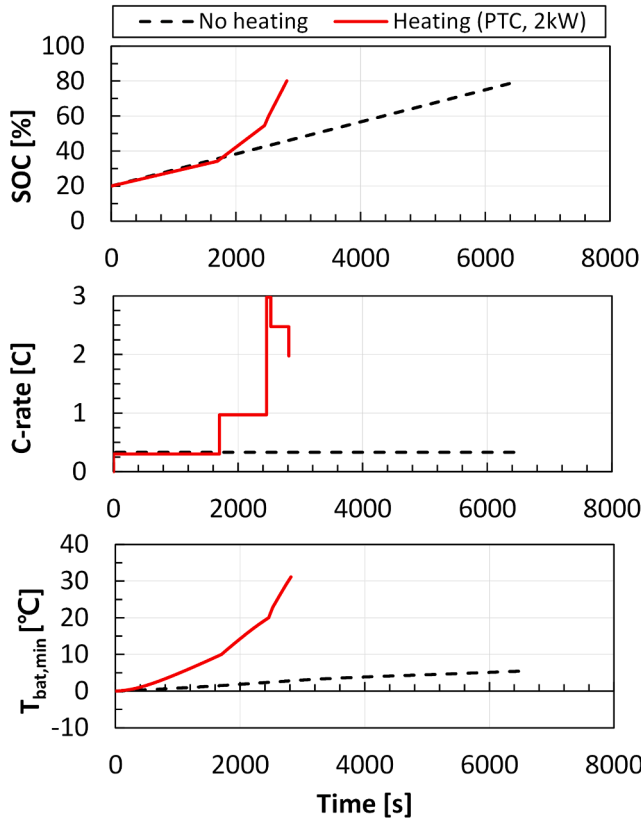
Modified fast-charge map based on Dai & Long [28].

SOC/ $T_{\min}$	-20 °C	-10 °C	0 °C	10 °C	20 °C	40 °C	45 °C	50 °C	55 °C	$V_{\text{cut-off}}^*$
0 %	0.05C	0.05C	0.05C	0.05C	0.05C	0.05C	0.05C	0.05C	0.05C	3.15 V
10 %	0.1C	0.2C	0.33C	1C	3C	3C	1C	0.5C	0.33C	3.639 V
20 %	0.1C	0.2C	0.33C	1C	3C	3C	1C	0.5C	0.33C	3.706 V
30 %	0.1C	0.2C	0.33C	1C	3C	3C	1C	0.5C	0.33C	3.743 V
40 %	0.1C	0.2C	0.33C	1C	3C	3C	1C	0.5C	0.33C	3.775 V
50 %	0.1C	0.2C	0.33C	1C	3C	3C	1C	0.5C	0.33C	3.815 V
60 %	0.1C	0.2C	0.33C	1C	2.5C	3C	1C	0.5C	0.33C	3.874 V
70 %	0.07C	0.2C	0.33C	1C	2.5C	3C	1C	0.5C	0.33C	3.965 V
80 %	0.07C	0.2C	0.33C	1C	2C	3C	1C	0.33C	0.33C	4.075 V
90 %	0.07C	0.1C	0.2C	0.6C	1C	1C	0.5C	0.2C	0.2C	4.12 V

* If the $T_{\min}$ exceeds 20 °C, the $V_{\text{cut-off}}$ is 4.12 V.**Table 5**

Simulation conditions for fast-charge with heating.

Parameter	Values
Ambient air temperature (°C)	0, -7, -20
State of charge (SOC, %)	20–80
Nominal battery capacity (Ah)	180
Volumetric flow rate of coolant (L/min)	10
PTC heater capacity (kW)	0–10
PTC heater efficiency η_{heater}	1
Target battery temperature (°C)	20
Battery type	NMC
Battery capacity (kWh)	64
Number of modules / cells	5 / 300

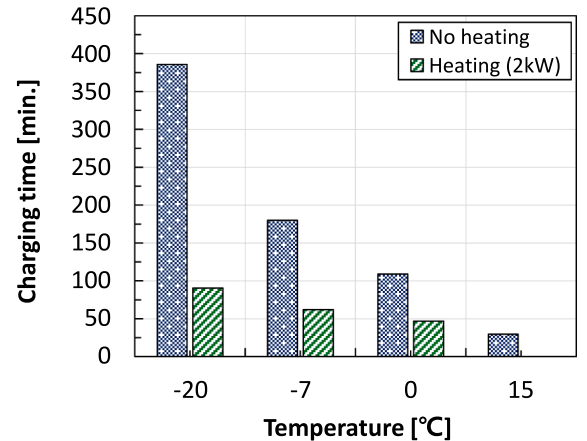
**Fig. 7.** Impact of heating on charging performance and battery temperature (0 °C, 2 kW).

approximately 2400 s, the C-rate decreased as the process transitioned to the next stage, which occurred when the SOC or cell voltage reached its predefined cut-off value.

Additional power is consumed for heating. In the ~1600-s range, the C-rate in the heating scenario was slightly lower than that in the no-heating condition. Although both scenarios exhibited the same battery temperature ranges in the charging map, some power in the heating scenario was allocated for heating. This slightly reduced the charging current. However, the difference was insignificant, and the rapid increase in the battery temperature significantly enhanced the charging rate. Consequently, the total charging time was reduced to 2816 s (47 min), shortening the process by 1 h and 3 min compared to that in the no-heating condition.

As shown in Fig. 8, the effect of heating became more significant as the temperature decreased. In the no-heating condition, the charging time was 29 min at 15 °C, but it increased to 1 h 50 min, 3 h, and 6 h 26 min at 0 °C, -7 °C, and -20 °C, respectively. During winter, especially at temperatures below -7 °C, even when connected to a fast charger, the charging speed drops to a level comparable to that of an AC charger. The green bars in Fig. 8 demonstrate that simply heating the battery during charging without preheating can achieve a substantial time savings of at least 57 %. Specifically, at 0 °C, -7 °C, and -20 °C, the charging times are reduced to 47, 62, and 89 min, respectively, which correspond to reductions of 57 %, 66 %, and 80 % compared to the no-heating condition.

Battery heating requires the power of the PTC heater to draw energy from the battery. As shown in Fig. 9, additional charging is required to compensate for the energy utilized by the heater. Because additional charging increases the overall cost, it is essential to analyze the reduction in charging time and the impact on charging fees associated with battery heating. Although charging costs vary by country, this study calculated the charging costs based on the cost per kWh in South Korea. In South Korea, the cost are determined based on the amount of energy charged. As of September 2024, the Ministry of Environment has set a

**Fig. 8.** Effect of heating during fast-charge on charging time at low temperatures (2 kW).

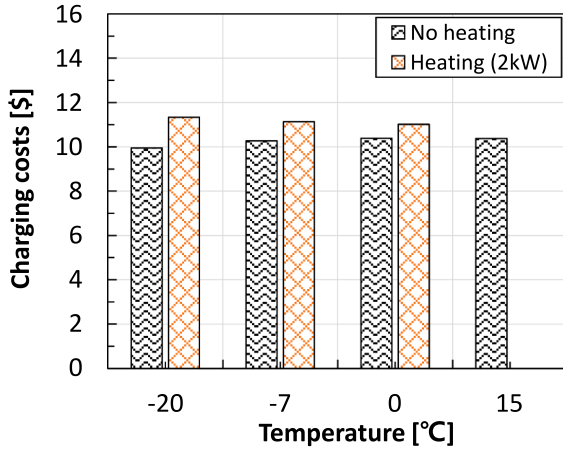


Fig. 9. Effect of heating during fast-charge on charging costs at low temperatures (2 kW).

cost of 347.2 KRW/kWh for DC fast chargers with a minimum power output of 50 kW. Applying an exchange rate of 1,324 KRW/USD, the charging cost was approximately 0.26 USD/kWh. The amount of energy required to charge the battery from 20 % to 80 % of the SOC depends on the battery capacity. Although the actual energy required may vary slightly depending on the thermal state of the battery, the battery used in this study had a capacity to charge approximately 40 kWh. Additionally, the energy consumed for battery thermal management incurs additional costs. Because the power consumed by the heater depends on the total heating time, longer charging and heating durations increase the costs. In this simulation, a heater with a power output of 2 kW and efficiency of one was used. For heating at -20°C , the additional energy consumption is calculated as $2\text{ kW} \times 1 \times 1.49\text{ h} = 2.98\text{ kWh}$, resulting in an additional cost of approximately 1 USD.

At -20°C , the longest heating time results in an additional charging cost of 1.39 USD, while the additional costs at -7°C and 0°C are 0.86 USD and 0.63 USD, respectively. In other words, charging with heating provides a 60 % reduction in the charging time for an additional cost of approximately 1 USD. Although the charging time at -20°C was significantly reduced by battery heating, the remaining 1 h and 30 min were still too long, according to fast-charge standards. To further reduce the fast-charge times under extremely cold conditions, it is necessary to analyze the effect of using a higher-power PTC heater to increase the battery temperature more rapidly.

3.2. Heating effects based on heater capacity for fast-charge time reduction

Fig. 10 shows the temperature variations of the battery and coolant when using a 4 kW heater. As the heater power increases, the coolant temperature rises more rapidly, and the time required for the battery's minimum temperature to reach 0°C is reduced from 1400 s with the 2 kW heater to 1000 s with the 4 kW heater. At 2200 s, when the battery minimum temperature reaches 20°C , the heater turns off. However, owing to the residual heat from the high coolant temperature and the heat generated by the high charging current, the battery minimum temperature continues to rise, reaching 37°C by the end of the charging process. The total charging time was reduced from 3728 s with a 2 kW heater to 2685 s with a 4 kW heater, saving approximately 17 min.

Increasing the heater capacity led to a reduced charging time. However, if the heater capacity is excessive relative to the battery system, the heater output decreases owing to the coolant temperature limit of 80°C , controlled by the PI algorithm. Fig. 11(a) shows the power consumption of the PTC heater. The heater operated at maximum output until 750 s, increasing the heat transfer rate to 5.3 kW. However, as shown in Fig. 11(b), the heater output decreases when the temperature

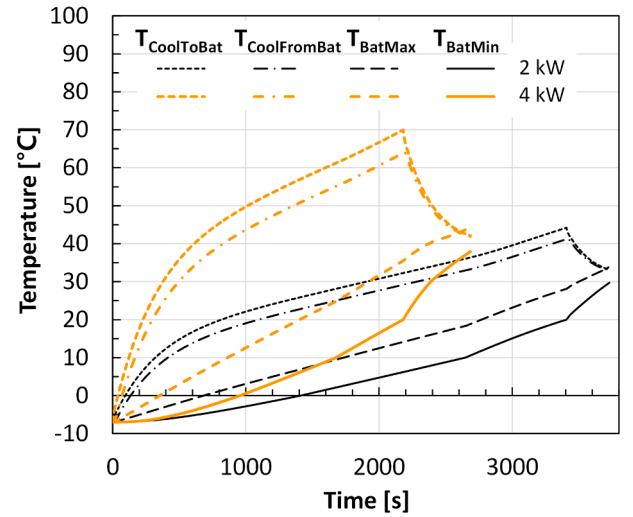


Fig. 10. Temperature of the battery and coolant based on heater capacity during fast-charge (-7°C , 2 kW, and 4 kW PTC heater).

of the coolant entering the battery pack reaches 80°C .

In fast-charge at moderate temperatures, high C-rates result in significant battery heat generation. In contrast, at low temperatures, although the internal resistance of the battery is high, the charging current remains low, as shown in Table 4, leading to minimal heat generation rates. As illustrated in Fig. 11(a), heat generation remains minimal, at only a few tens of watts, below 10°C , and even in the range of 10 – 20°C , it reaches approximately 1 kW, which is insufficient to significantly contribute to battery heating. Once the battery reaches 20°C , however, heat generation increases significantly to 8 kW, eliminating the need for additional external heating. This is why the battery heating cut-off temperature was set to 20°C in this study.

Using a high-capacity heater solely to reduce the charging time under low-temperature conditions may not be cost effective because it could significantly increase vehicle production costs. Therefore, each battery system requires an appropriately designed heater capacity to balance the performance and cost. The charging time was analyzed based on the heater capacity.

Fig. 12 shows the simulation results for the charging time and charging costs based on heater capacity. Consistent with the previous findings, increasing the heater capacity reduced the charging time. With heaters of 4 kW or higher, the battery could be fully charged within an hour under all low-temperature conditions. However, as the heater capacity increased beyond a certain point, the reduction in charging time diminished, and depending on the ambient temperature, the charging time did not fall below 30, 35, or 45 min. This outcome is influenced by factors like the target battery temperature, thermal limits of the battery, and coolant temperature constraints, which vary depending on the battery system and the charging current map. Therefore, EV manufacturers must design heater capacities to suit specific battery systems.

The charging costs also varied with the heater capacity. Although larger heaters require higher costs owing to their increased power consumption, they increase the battery temperature more quickly, thereby reducing the heating time. Consequently, despite the initial expectation of higher costs, the reduction in heating time offsets some of the expenses, making the overall cost increase less significant than anticipated. As the heater capacity increases, the charging costs converge toward a particular value depending on the ambient temperature, following a trend similar to that of the charging time.

The temperature difference between the cells is also a critical parameter in a BTMS. Typically, a BTMS aims to maintain this temperature difference within 5°C . Feng et al. [40] suggested a method for analyzing how variations among cells arise because of temperature

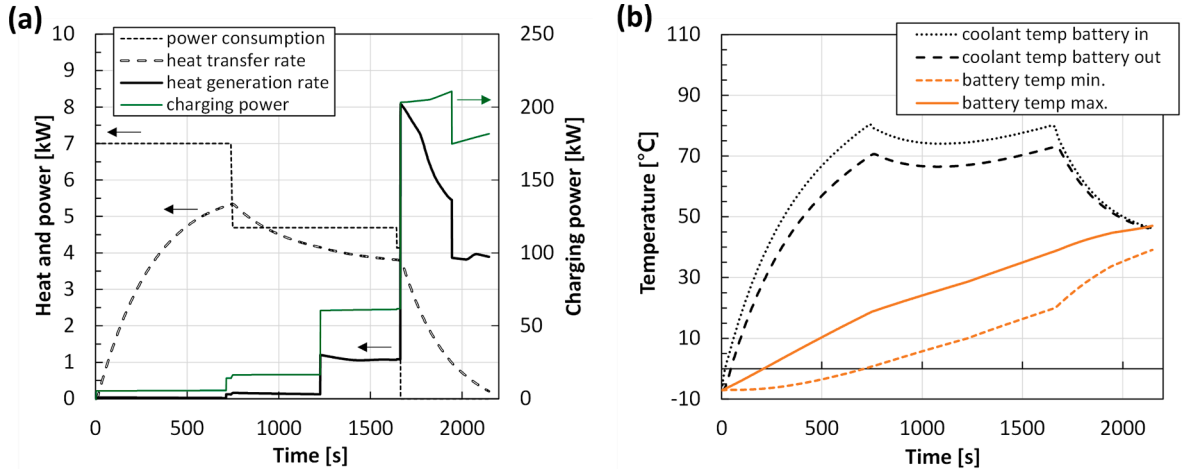


Fig. 11. Heat, power, and temperature profiles during fast-charge with 7 kW heating (-7°C); (a) Heater power, charging power, heat transfer rate to the battery, and heat generation of the battery (b) Coolant temperature at battery pack inlet and outlet and battery temperatures.

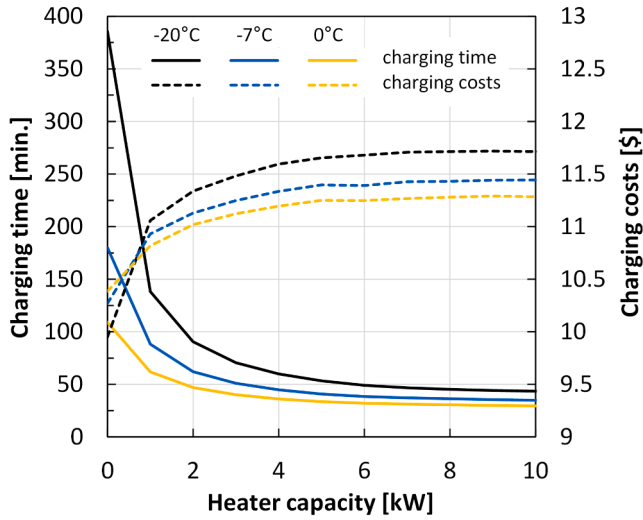


Fig. 12. Charging time and costs as a function of heater capacity at different temperatures.

nonuniformity within the battery pack. Their findings indicated that increasing the temperature difference by 5°C could lead to a 1.5–2 % reduction in the overall capacity of the pack. Yang et al. [41] found that the temperature differences between cells had less impact on the overall voltage output and discharge capacity of the battery pack. However, larger temperature differences increase the discharge imbalance, accelerating the capacity loss rate, and contributing to battery aging. Choi et al. [42] and Jun et al. [27] conducted research on reducing the temperature differences under battery preheating conditions and improving battery–coolant heat exchanger designs to enhance the heat transfer efficiency.

Under the same battery pack heat exchanger conditions, increasing the heater capacity increases the total heat transfer rate. However, it also increases the temperature difference between the cells because of the temperature difference between the coolant inlet and outlet. Fig. 13 shows the inter-cell and inner-cell temperature differences according to the ambient temperature and heater capacity.

For the temperature distribution within each cell, thermal nodes were constructed into a 2×3 grid, as illustrated in Fig. 2. The temperature differences were calculated at six points per cell, and the maximum temperature difference among these points was obtained as the temperature difference for the inner cells. To determine the

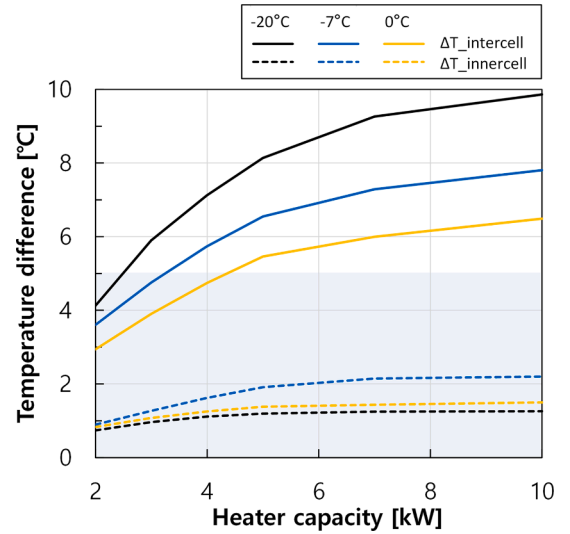


Fig. 13. Temperature difference between cells and inner cells according to heater capacity and ambient temperature.

temperature difference between cells referred intercell temperature difference, the representative temperature of each cell was calculated as the average of the six nodal temperatures, and the difference was then decided between these representative values.

The temperature difference within the battery cells arises due to the low thermal conductivity of the cells, particularly in the cross-plane direction. As shown in Table 1, especially the cross-plane thermal conductivity ($0.8 \text{ W/m}\cdot\text{K}$) is even lower than that of insulation case ($1.5 \text{ W/m}\cdot\text{K}$), which contributes to limited heat transfer between cells. This low thermal conductivity is a material characteristic and it can delay thermal runaway at high temperature. To improve the heat transfer rate and address temperature imbalances, a double-layer channel design can be considered.

For each case, the maximum temperature difference at each time step was determined, and the representative value was selected as the average of the maximum differences over the entire charging time. At 0°C , using a heater with 4 kW or more, at -7°C with 3 kW or more, and at -20°C with 2 kW or more exceeds the target temperature difference of 5°C . This indicates that the current cell-to-coolant heat exchanger design creates significant intercell temperature differences under extremely cold conditions. Therefore, it is necessary to redesign the coolant channels when the heater capacity is increased to reduce

charging time.

3.3. Effects of including single heating on fast-charge performance

The following is an analysis of the effects of single heating. Ideally, preheating the battery while driving before arriving at a fast-charge station would optimize fast-charge; however, this may not always be feasible owing to short distances to the station or other constraints. The analyses presented in the previous figures show that simultaneous heating during fast-charge can effectively reduce the charging time, even without prior preheating. Some studies have proposed a strategy in which the vehicle is connected to a charger and the battery temperature is raised to a certain level using power from the charger before the charging process begins. Both these studies and the present one considered scenarios without preheating during driving. However, the primary difference is that this study focused on initiating heating simultaneously with the start of charging, whereas the alternative strategy involves preheating the battery before charging commences. This approach is referred to as the preheating stage or the single-heating stage.

Ye et al. [43] found that, when charging starts at low SOC levels, the power from the charger can be allocated to a single-heating step, enabling higher C-rates to reduce the charging time. The preheating stage lasted approximately 2200 s, raising the ambient temperature from -20°C to -1°C . Liu et al. [44] investigated using a stage referred to as single heating, which occurs before charging, to preheat batteries under low-temperature conditions. In their study, a 9 kW PTC water heater was used to raise the battery maximum temperature from an

ambient temperature of -10°C to 1°C before initiating charging. During the charging process, heating continued until the battery temperature reached 21°C , after which pure charging proceeded without additional heating. Their results showed that charging from 4 % to 80 % SOC under these conditions required 80 min. During charging without single heating, the total charging time was 95.5 min. However, by including a single-heating stage, the total charging time was reduced to 80 min, even after considering the time spent on single heating. In line with these findings, this study also analyzed the fast-charge process under low-temperature conditions, including a single-heating stage.

In this analysis, the SOC was started at 25 % and was charged to 80 %. Under ambient temperature conditions of -20°C , single heating is first conducted until the battery minimum temperature reaches 1°C . Afterward, heating continues along with charging until the temperature reaches 21°C , followed by pure charging without additional heating. Fig. 14(a) shows the case of heating during fast-charge without single heating. Initially, 6 kW of power was supplied from the charger, with 2 kW used by the PTC heater and the remaining 4 kW allocated for battery charging. By contrast, Fig. 14(b) presents a scenario with a single-heating stage in which no charging occurs for the first 58 min. Once the minimum temperature of the battery reached the required level, charging began at 19 kW because 2 kW of the 21 kW supplied was utilized for heating. Comparing the SOC progress in Fig. 14(c), the battery reaches a higher charging power after a single-heating cycle, resulting in a shorter pure charging time. However, from the perspective of the EV owner, the time spent on single-heating is an effective part of the total charging time. Consequently, the total charging time was shorter in the case without single heating, taking 89 min —approximately 6 min less

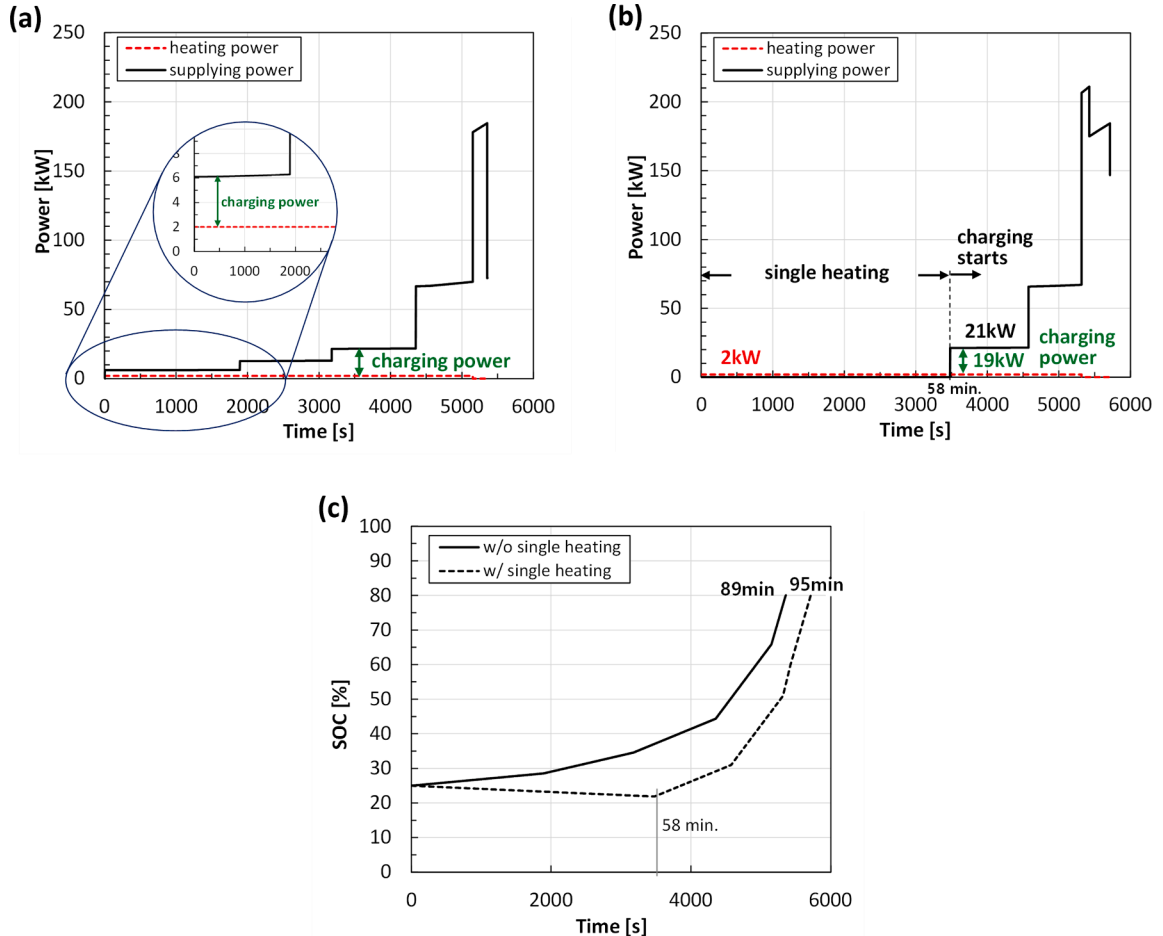


Fig. 14. Fast-charge analysis under different heating processes (-20°C , 2 kW, SOC 25–80 %); (a) Supply and heating power during charging without a single-heating stage (b) Supply and heating power during charging with a single-heating stage (c) SOC during charging with and without a single-heating stage.

than that in the single-heating scenario.

However, the analysis results may vary depending on heater capacity. Liu et al. [44] used a 9 kW PTC heater. Fig. 15 presents the fast-charge results when a 9 kW heater, which is larger than the design capacity of the BTMS in this study, is applied. In the case of heating without single heating, the charging power at -20°C , based on the charging map (Table 4), was limited to 6 kW at that SOC. As the heater consumes 9 kW, the battery undergoes a temporary discharge instead of charging. This discharge continued for approximately 500 s until the rising battery temperature allowed for an increased charging current and the battery began to charge. When a single-heating stage was included, a pattern similar to that shown in Fig. 14(b) was observed. As the heater capacity increased, the single-heating time decreased to 21 min; however, the higher power consumption led to a faster decrease in the SOC. Ultimately, as shown in Fig. 15(c), the total charging times were nearly identical for both cases, that is, 43 and 44 min.

As shown in Fig. 16(a), higher ambient temperatures and an increased heater capacity reduced the single-heating time. However, the greater power consumption and additional time required for single heating result in overall charging times that are comparable to or even longer than those without single heating, as illustrated in Fig. 16(b). Notably, the overall charging performance can vary depending on various factors, such as the battery-coolant channel design, temperature control objectives, or coolant flow rate within the BTMS.

While charging costs remain negligible, the single heating slightly increases cell voltage, resulting in an additional cost of approximately 0.6 USD at -20°C on average compared to charging without single

heating. Although incorporating a single-heating stage can reduce the total charging time compared with no heating, the time spent on a single-heating stage must also be considered, which limits its applicability across all charging scenarios. For instance, if an EV owner with only 30 min available visits a fast-charge station, single heating may consume valuable time without charging the battery, potentially lowering the SOC.

4. Conclusion

As the charging speed of battery-powered electric vehicles (BEVs) is limited by the in-vehicle battery management system (BMS) based on battery temperature, achieving optimal battery heating to a temperature range of 20°C to 45°C is crucial to reduce fast-charge times. Compared to conventional BEV battery heating systems, which were previously designed to target only 0°C to 5°C , more heat is required for reducing fast-charge times. With the growing need for active battery heating strategies in BEVs, new battery thermal management system (BTMS) are being explored, including heat pumps with vapor injection, and the utilization of waste heat from motors and inverters.

As a foundation study, this paper evaluates the heating load required to enhance the fast-charge performance and examines the impact of heating capacity on charging times, costs, and battery cell temperatures. While optimizing coolant channel designs in coolant plate to increase heat transfer rate to battery is important, assessing the influence of heating capacity within an existing coolant design is crucial for developing an integrated thermal management system for BEVs. This research

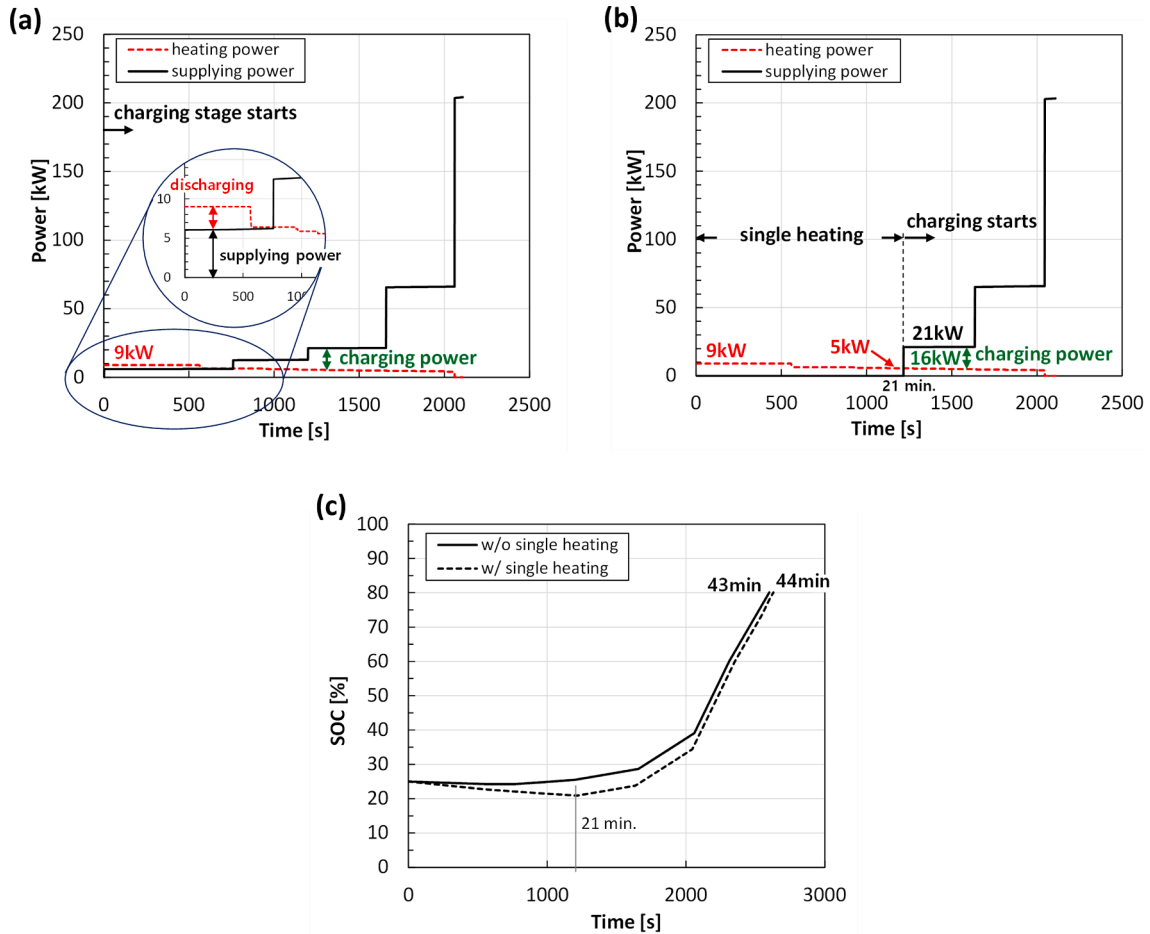


Fig. 15. Fast-charge analysis under different heating processes (-20°C , 9 kW, SOC 25–80 %): (a) Supply and heating power during charging without a single-heating stage (b) Supply and heating power during charging with a single-heating stage (c) SOC during charging with and without a single-heating stage.

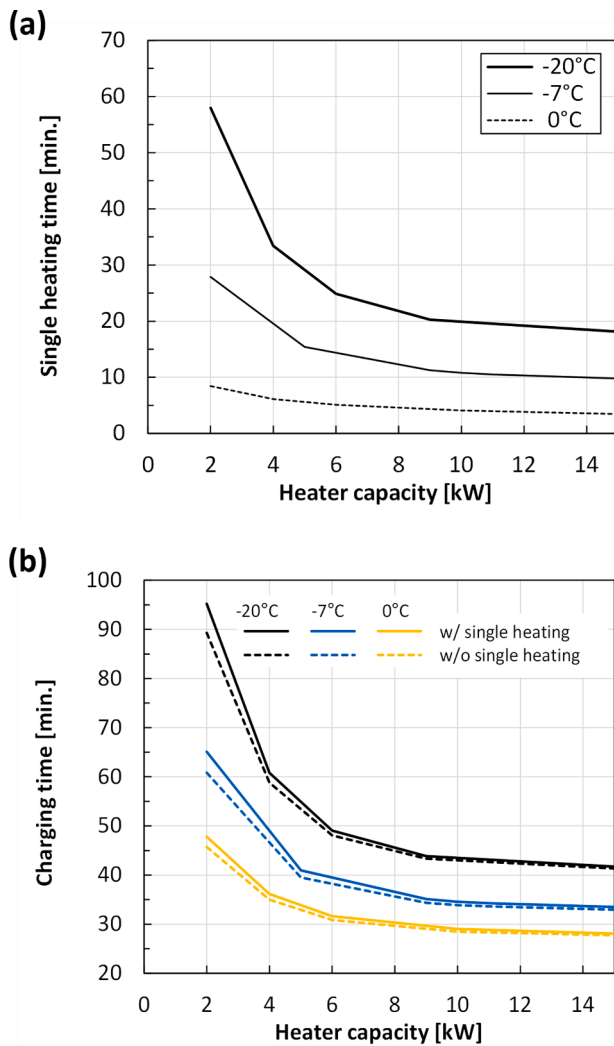


Fig. 16. Effects of single-heating based on heater capacities and ambient temperatures (SOC 25–80 %); (a) Single-heating time according to heater capacity at different ambient temperatures (b) Total charging time according to heater capacity with and without a single-heating stage.

provides valuable insights into managing the heat flows of the entire vehicle, ensuring effective thermal management for both the cabin comfort and battery performance.

To evaluate heating capacity under conditions that account for heat transfer from coolant to battery, heat loss to ambient, and heat generation rates during fast-charge, this study developed an equivalent circuit model of the battery and a thermal model of a conventional PTC heater-based BTMS. Simulations were conducted for different heating load scenarios, including heating during fast-charge and single-heating at a fast-charge station where the power of the DC charger can be utilized. The results are summarized as follows:

- Heating during charging improves performance by increasing the battery temperature, which increases the charging power and reduces the charging time. At -7°C , charging time decreases from 3 h without heating to 62 min with heating. Although some power is diverted for heating, the overall charging process is much faster. While heating increases the charging costs, the additional expense remains modest at approximately 1 USD across all temperature conditions. To further shorten the charging time under extremely cold conditions, it is necessary to increase the heater capacity within the current BTMS.

- Increasing the heater capacity, by using a 4 kW heater, reduces charging time and improves battery performance by reaching optimal temperatures faster, saving 17 min compared with using a 2 kW heater. However, larger heater capacities increase the temperature differences between cells, potentially affecting battery durability. Beyond a certain point, the impact of additional capacity diminishes as the charging times converge. A 4 kW heater ensures that fast-charge can be completed within 60 min, even under extremely cold conditions. Although higher capacities increase energy consumption, shorter heating periods help offset the additional costs. The heater capacity must be carefully optimized because an increased capacity does not always guarantee faster charging across all conditions.
- Single-heating of the battery before charging helps reach optimal temperatures faster but adds energy and time costs, making it less practical in some situations. When EV owners have limited time at fast-charge stations, starting heating simultaneously with charging is more effective. Single heating can also delay charging and lower the SOC, thereby reducing the session efficiency. These results may vary depending on the BTMS design and its control strategies.

Overall, the model proposed in this study reflected the thermal characteristics of the battery during fast-charge and enabled the analysis of the impact of heating capacity. It confirmed that increasing heater capacity can reduce charging times at low temperatures including extremely cold conditions. However, its impact on charging efficiency and potential temperature imbalances must be carefully evaluated. These findings will accelerate the investigation of active battery heating strategies and integrated EV thermal management systems for the cabin, powertrain, and battery. Additionally, they will support the widespread adoption of BEVs by reducing charging times across diverse climates.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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