Energy Proceedings
Vol 54, 2025
ISSN 2004-2965

Simulation of thermal management in square battery systems using CPCM/liquid cooling and topology optimization of fins#

Lin Liu[1,2], Jiali Liu[1,2], Xinli Lu[1,2*], Wei Zhang[1,2], Dongxi Liu[1,2], Shuntao Hu[1,2]

1 Tianjin Geothermal Research and Training Center, College of Mechanical Engineering, Tianjin University, Tianjin 300350, China

2 State Key Laboratory of Engines, Tianjin University, Tianjin 300350, China

(Corresponding Author: xinli.lu@tju.edu.cn)

ABSTRACT

In the present era, electric vehicles are progressively gaining popularity on a global scale. The objective of using a battery thermal management system (BTMS) is to ensure that the power battery pack maintains a controlled temperature range during both charging and discharging processes. This paper aims to enhance the performance of the BTMS by incorporating topologically optimized fins into the composite phase-change material (PCM) and liquid cooling coupling BTMS. Specifically, paraffin with expanded graphite (EG) and foam aluminum nitride as composite phase-change materials were selected. Utilizing COMSOL Multiphysics software, topology optimization was employed to determine the material distribution within the design domain. Subsequently, a 3D model was constructed and the performances of three systems—without fins, with rectangular fins, and with topology-optimized fins—were compared. The results show that after 720 s of discharging at a 5C charge/discharge rate, the average temperature of the battery with the topology optimized fin system is 15.16 °C lower than that of the battery without fins and 1.32 °C lower than that of the battery with rectangular fins. This indicates that the system with topology optimized fins has better heat transfer efficiency.

Keyword: liquid cooling, topology optimization, electric vehicle, phase-change material

NONMENCLATURE

Abbreviations	
CPCM	Composite Phase Change Material
BTMS	Battery Thermal Management System
EG	Expanded Graphite

1. INTRODUCTION

In view of the ongoing changes in the global environment and climate, many countries have acknowledged the importance of conserving energy and reducing emissions. Fossil fuels contribute to 80% of the world's energy consumption, and their widespread use is a major contributor to global warming. The combustion process releases greenhouse gases and harmful pollutants, causing significant damage to the environment[1]. Electric vehicles, as opposed to gasoline cars, generate no emissions and minimal pollution, leading to their increasing popularity. In China, the sales and ownership of new energy electric vehicles have shown a clear upward trajectory in recent years. However, with the rising number of individuals purchasing and operating electric vehicles, there has been a surge in incidents caused by thermal runaway of the battery pack resulting in fires. The current predominant power source for electric vehicles is lithium-ion batteries. Thermal runaway in these batteries can occur as a result of increased heat generation during vehicle operation or charging, leading to localized overheating if not dissipated promptly. As the temperature rises, the electrical conductivity of the electrolyte in lithium-ion batteries increases, resulting in heightened current flow and subsequent heat accumulation. This positive feedback loop is a key factor contributing to thermal runaway[2]. Therefore, the implementation of a BTMS is essential to ensure the safe and stable operation of electric vehicles.

Today, battery thermal management systems have undergone decades of development and are generally divided into two categories: active cooling and passive cooling. Active cooling mainly includes air cooling and water cooling, while passive cooling involves phase change material thermal management and heat pipe thermal management. Among these, liquid-cooled BTMS uses low-temperature fluid as the coolant to absorb heat, resulting in higher efficiency in heat transfer compared to air-cooling systems. Jarrett and Kim[3, 4] performed modeling and optimization of the routing, width, and length of the cooling plate channels,

This is a paper for the 16th International Conference on Applied Energy (ICAE2024), Sep. 1-5, 2024, Niigata, Japan.

focusing on pressure drop, average temperature, and temperature uniformity as the objective functions. They also conducted an assessment of the optimized design's sensitivity to boundary conditions. Furthermore, there has been significant progress in the field of thermal management applications with the rapid advancement of PCM, particularly composite phase change materials with high latent heat, due to their capacity to efficiently absorb the substantial amount of heat generated by lithium batteries. The thermal management scheme proposed by Ping et al.[5] was based on a PCM-fin structure for square batteries, and the cooling effects of air, fin, pure phase change material, and composite cooling on individual lithium-ion batteries were examined through simulation calculations.

Meanwhile, numerous scholars have integrated the liquid cooling system with PCM to develop a more advanced BTMS. Chen et al.[6] investigated the impact of EG content in CPCM on heat dissipation by modifying the composition of CPCM along the flow direction. They segmented the entire system into three sections with lengths of 110 mm, 120 mm, and 120 mm, effectively constraining the maximum temperature and temperature difference of the battery to 46.35 °C and 3 °C, respectively. After employing the non-uniform heat generation model, Ping[7] established a linked system involving phase change material and liquid pipes. This system incorporated CPCM into the battery pack and arranged the liquid cooling pipes in a staggered pattern. The results indicated that the system displayed outstanding cooling capabilities at 45 °C, maintaining the maximum temperature of the battery pack at 47 °C with a temperature difference of 4.5 °C. Zhang et al.[8] investigated the impact of adding fins to a coupled system and demonstrated that the strategic incorporation of fins can effectively mitigate temperature rise. The maximum temperature of the system decreased by 1.4 °C, while the maximum temperature differential reduced by 0.3 °C.

The aforementioned literature discusses various BTMS studies, and in the context of structural optimization, topology optimization can be employed as a means to enhance system performance. Topology optimization was initially introduced by Bendsøe and Kikuchi[9] in 1988. It fundamentally involves a method for material allocation based on the establishment of target functions and constraints[10, 11]. Initially employed for addressing issues in structural mechanics[12], topology optimization of continuum structures has seen significant development in recent years, leading to its widespread application across various fields of physics. Bruns[13] utilized topology optimization in the context of heat transfer, taking into account the impact of heat conduction, convection, and radiation on the optimization process. Zeng et al.[14] conducted a topology optimization study on a forced convection air heat exchanger, followed by manufacturing and experimental validation of the optimized structure. The findings indicate that the topological structure can achieve enhanced heat transfer performance with the same pump power. The growth pattern of ferns was simulated by An et al. [15] to develop a biomimetic water-cooled thermal management system for 26,650 lithium-ion batteries using composite materials. They also conducted research on the impact of diameter, number of layers, and flow channel arrangement of the biomimetic microchannels on the highest temperature and temperature difference of the battery at a 4C discharge rate through numerical simulation and physical experiments.

After thorough analysis, it can be concluded that the liquid-cooled coupled CPCM battery thermal management system has made significant advancements and demonstrated superior efficiency in thermal management when compared to a single thermal management system. The optimization of this system can be further explored from the perspectives of materials, cooling fluid, and structure. In order to enhance the structure of the BTMS, this paper delves into topology optimization design for the fins within the system with the aim of achieving higher heat transfer efficiency within the same volume design domain. Subsequently, a comparison is made between the heat transfer performance of the system equipped with the new fin system and that of a regular fin system, followed by an analysis on how topology-optimized fins improve heat transfer performance.

2. NUMERICAL SIMULATION MODEL

2.1 Geometric model

The BTMS model depicted in *Fig. 1* is investigated in this paper. To mitigate computational complexity and reduce calculation time, the analysis is performed using a periodic battery unit instead of modeling the entire battery pack. During the charging and discharging process, heat generated by the battery is initially transferred to both sides of the CPCM, followed by dissipation through a liquid cooling tube containing cold fluid. The heat transfer between the cold fluid and CPCM can be enhanced by incorporating fins on the external surface of the liquid cooling tube. It is anticipated that optimizing the fin structure will further enhance the overall performance of the BTMS.

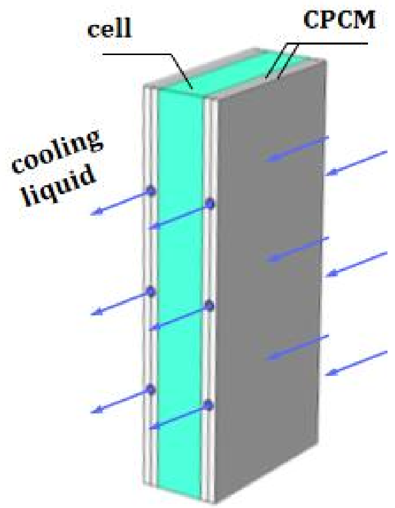

Fig. 1 Investigated BTMS

The battery under investigation in this paper is a 15Ah square lithium iron phosphate battery, characterized by its volume dimensions of 140 mm×65 mm×18 mm. As the focus of this paper lies in designing the heat dissipation structure for the battery, the internal heat generation principle is not the primary research objective. Therefore, a homogenized parametric model is employed to represent an individual battery in this paper; wherein a single battery is considered as a constant heat source and its heat output per unit volume and physical property parameters are obtained from relevant literature references[16]. Data can be found in *Table. 1* and *Table. 2*.

Table. 1 Physical property parameters

Parameters	Data
Rated capacity/(Ah)	15
Rated voltage/(V)	3.2
Internal resistance/(mΩ)	4
Charging current/(C)	0.5

Table. 2 Heat output per unit volume

Discharge rate	Electric current/A	Heat output per unit volume/(W/m^3)	Heat flux/(W/m^2)
1C	15	15935	287
2C	30	42858	771
3C	45	80769	1454
4C	60	129670	2334
5C	75	189560	3412

The liquid cooling tube's axial cross-section is utilized as the foundational model for conducting topology optimization. Following this, the optimized structure can be expanded into a 3D model and assessed for its impact on optimization. To maintain symmetry within the physical model, the quarter design domain illustrated in *Fig. 2* is retained for modeling purposes, and symmetric treatment can be applied to achieve a complete fin. In order to ensure symmetry and rationality in the fin structure, any uneven heat distribution in convective heat transfer is disregarded, with a uniform heat source being employed within the design domain to simulate the fin's heat transfer process.

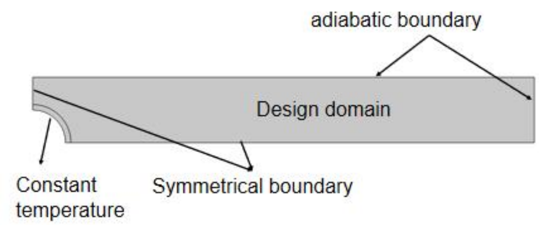

Fig. 2 Design domain

2.2 Numerical model

To facilitate the calculation, the following assumptions are proposed for the model: 1) It is assumed that there is negligible radiation heat transfer and contact thermal resistance at the thermal interface; 2) During the phase change process, it is assumed that there is no natural convection occurring within the phase change material; 3) The physical property parameters of the phase change material are assumed to remain constant in both solid and liquid phases; 4) Uniform heating of a single battery is assumed; 5) Water is considered as an incompressible fluid; 6) The fluid flow inside the tube is treated as fully developed.

In a liquid cooling tube, the conservation equation for the cold fluid's energy :

$$\frac{\partial}{\partial \tau}(\rho_w c_w T_w) + \nabla(\rho_w c_w \vec{v} T_w) =- \nabla(K_w \nabla T_w) \tag{1}$$

In this equation, ρ_w , c_w and T_w represent the density, specific heat, and temperature of the cooling water respectively. $\vec{v}$ is the velocity of the water.

The cold fluid adheres to the principle of momentum conservation with its corresponding equation:

$$\frac{\partial}{\partial \tau}(\rho_w \vec{v}) + \nabla(\rho_w \vec{v}\vec{v}) =- \nabla p \tag{2}$$

In this equation, *p* is the static pressure of cooling water.

The equation governing the continuity of cooling water is:

$$\frac{\partial \rho_w}{\partial \tau} + \nabla(\rho_w \vec{v}) = 0 \quad (3)$$

Topology optimization employs a variable density method to adjust the material distribution within the structure while ensuring compliance with constraints, in order to achieve an optimal structural shape. To determine the optimal material distribution based on a given objective function, a design variable is assigned to each finite element, ranging from 0 (no material) to 1 (solid material). In this study, topology optimization utilizes the SIMP difference model penalty for intermediate values in order to obtain improved material distribution.

The relationship of elastic modulus is:

$$E_i(x) = E_0 + x_i^p(E_1 - E_0) \quad (4)$$

In this equation, x_i represents the unit density, $E_i(x)$ denotes the elastic modulus after interpolation, E_0 stands for the elastic modulus at 0 unit density, E_1 signifies the elastic modulus at unit density of 1, and *p* is the penalty parameter.

The objective of this paper is to optimize heat transfer performance within the specified design domain：

$$Min:\ f_0(x) = \int_{\Omega} k(\nabla T)^2\, dV \quad (5)$$

$$\begin{cases} F(T(x), x) = 0 \\ \int_{\Omega} \gamma\, dV \le \phi \int_{\Omega} dV \\ 0 \le \gamma \le 1 \end{cases} \quad (6)$$

$$x \in X = \{x_1, x_2, x_3, \dots, x_n\}$$

In the equation, x represents the position of the design variable. The first constraint condition specifies that the design variable must adhere to the physical model. The second constraint condition limits the upper bound of total solid material distribution and restricts the use of high thermal conductivity materials by setting a value. The third constraint condition confines the range of the design variable.

2.3 Initial and boundary conditions

The initial temperatures of the battery pack, phase change material, and coolant inlet are set to the ambient temperature of 25 °C. To evaluate the heat dissipation performance of the battery pack under extreme conditions, a discharge at a 5C rate for 720 s results in a heat dissipation of 189560 W/m^3. The inlet and outlet boundary conditions for the coolant are defined as velocity inlet and pressure outlet, with an inlet velocity set to 0.15 m/s and the static pressure at the pressure outlet set to 0 pa. A heat flux of 3412 W/m^2 is applied to simulate outer wall heating for the CPCM.

In the 2D topology optimization model, the inner radius of the pipe is 1.5 mm and the outer radius is 1.75 mm. The temperature at the inner pipe wall is set to 25 °C, while the heat source is specified as 1×10^6 W/m^3. Set the maximum output volume factor to 0.125.

3. RESULT and ANALYSIS

3.1 Pipe spacing

This paper examines the influence of pipe positioning on cooling efficiency, with the pipe spacing set at $\frac{L}{3}$ and $\frac{L}{4}$ in two different scenarios. It is assumed that each cooling pipe maintains its cooling function for the $\frac{L}{3}$ area, serving as the basis for topology optimization calculations. After conducting these calculations and applying symmetrical treatment, *Fig. 3* illustrates the topology-optimized structure of a single pipe in the first scenario.

Fig. 3 Pipe in the first scenario

The topology-optimized structure of the middle pipe in the second scenario mirrors that of the first scenario, resulting in an identical topology-optimized outcome also shown in *Fig. 3*. However, due to left-right asymmetry within the design domain for side pipes, only one half of their area undergoes topology optimization calculation before being symmetrically treated, as depicted in *Fig. 4*.

Fig. 4 Side pipes in the second scenario

The 2D topological optimization results are then extended to be integrated into the 3D BTMS model. The 3D model of the second scenario is presented in *Fig. 5*. Grid independence validation for the 3D model was carried out using the average battery temperature at the end of heat release as a reference, with results shown in *Fig. 6*. A significant alteration in data was noted when the grid number reached 3.3×10^6 compared to 8.5×10^5 grids, while less variation occurred with an increase to 5.5×10^6 grids. However, due to the high computational costs associated with 5.5×10^6 grids, calculations were conducted using a grid number of 3.3×10^6.

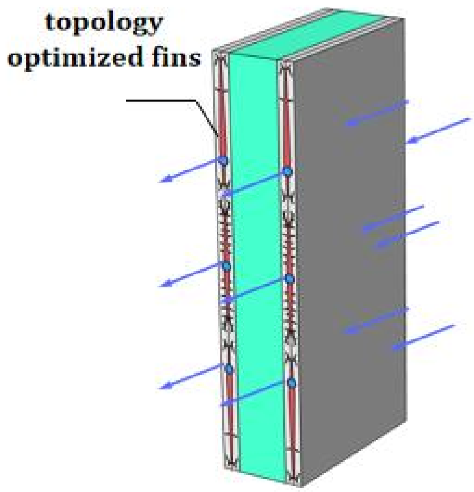

Fig. 5 The second scenario

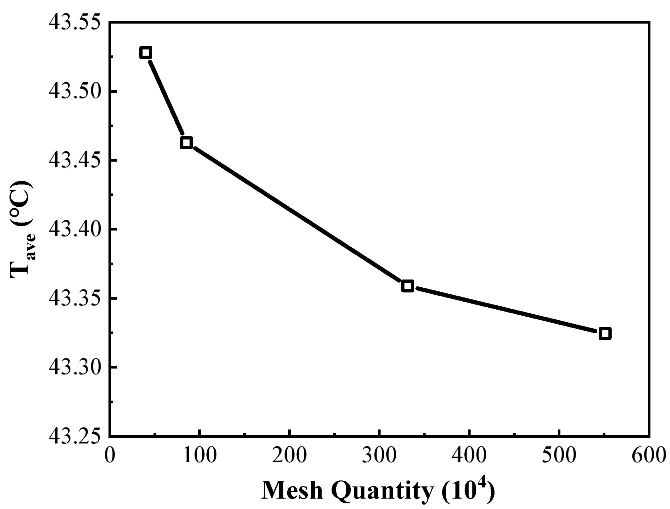

Fig. 6 Grid independence validation

The calculated results of the optimized two BTMS models illustrate the evolution of average battery temperature over time, as depicted in *Fig. 7*. It is evident from the graph that in both tube spacing designs, the battery temperature experiences an initial rapid increase followed by a gradual slowdown. This deceleration in average temperature rise can be attributed to the phase change material absorbing some of the heat generated by the battery. Additionally, it is observable from the figure that the temperature rise of the battery in the second scenario is less pronounced than that in the first scenario. Consequently, it can be inferred that the second scenario exhibits superior heat dissipation performance compared to the first scenario, indicating that a tube spacing of $\frac{L}{4}$ should be chosen for further research.

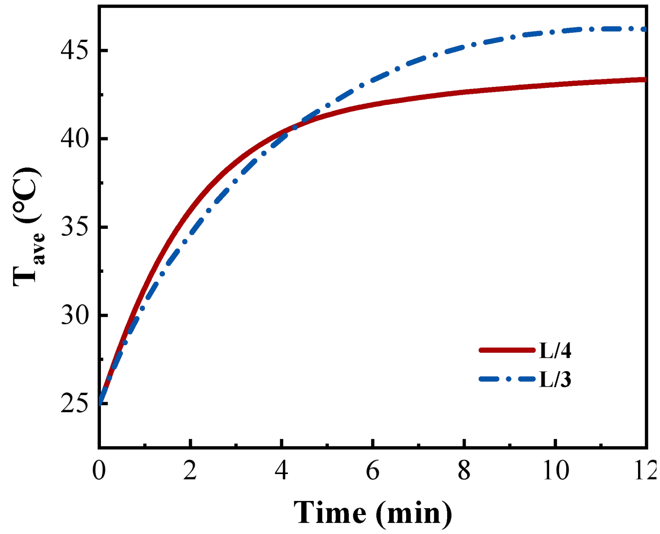

Fig. 7 Average battery temperatures (different pipe spacing)

3.2 Fin shape

This section presents a comparative analysis of the thermal performance when incorporating topological optimization fins, no fins, and rectangular fins to investigate the heat transfer efficiency of topological fins. The models without fins and with an equivalent volume of rectangular fins were analyzed separately. The results depicting the average temperature of the battery over time for different fin configurations are illustrated in *Fig. 8*.

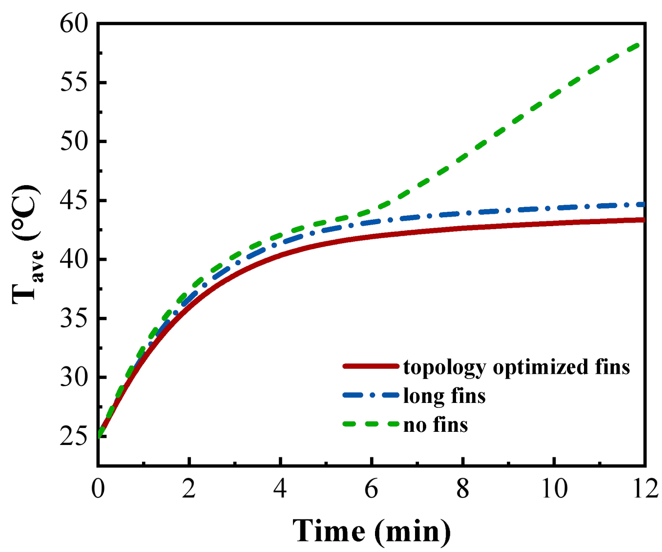

Fig. 8 Average battery temperatures (different fins)

It is evident from the figure that, compared to the scenario without fins, integrating topological optimization fins leads to a reduction in the average battery temperature by 15.16 °C. Notably, adding topological optimization fins outperforms incorporating an equal volume of rectangular fins in terms of heat transfer efficiency, resulting in a 1.5 °C lower average battery temperature after 720 s discharge. This underscores the superior heat transfer performance offered by topological fins as opposed to rectangular ones.

4. CONCLUSION

This paper has investigated a BTMS that integrates liquid cooling and CPCM using numerical simulation methods. The BTMS is enhanced with topology-optimized fins. Simulation results demonstrate that the BTMS equipped with topology-optimized fins exhibits superior temperature control performance compared to configurations without fins or with rectangular fins. Under a 5C charging and discharging rate for 720 s, the average battery temperature in the BTMS with topology-optimized fins is reduced by 15.16 °C compared to the BTMS without fins, and by 1.32 °C compared to the BTMS with rectangular fins. The BTMS integrates both active and passive cooling methods, and utilizes topology-optimized fins with enhanced efficiency within the same volume to regulate the battery temperature within an acceptable range. This system is deemed viable; however, further experimental study is necessary to verify its actual feasibility.

REFERENCES

[1] Du K, Calautit J, Wang Z, Wu Y, Liu H. A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges. Applied Energy. 2018;220:242-73.

[2] Rao Z, Wang S, Wu M, Lin Z, Li F. Experimental investigation on thermal management of electric vehicle battery with heat pipe. Energy Conversion and Management. 2013;65:92-7.

[3] Jarrett A, Kim IY. Design optimization of electric vehicle battery cooling plates for thermal performance. Journal of Power Sources. 2011;196:10359-68.

[4] Jarrett A, Kim IY. Influence of operating conditions on the optimum design of electric vehicle battery cooling plates. Journal of Power Sources. 2014;245:644-55.

[5] Ping P, Peng R, Kong D, Chen G, Wen J. Investigation on thermal management performance of PCM-fin structure for Li-ion battery module in high-temperature environment. Energy Conversion and Management. 2018;176:131-46.

[6] Chen X, Zhou F, Yang W, Gui Y, Zhang Y. A hybrid thermal management system with liquid cooling and composite phase change materials containing various expanded graphite contents for cylindrical lithium-ion batteries. Applied Thermal Engineering. 2022;200.

[7] Ping P, Zhang Y, Kong D, Du J. Investigation on battery thermal management system combining phase changed material and liquid cooling considering non-uniform heat generation of battery. Journal of Energy Storage. 2021;36.

[8] Zhang F, Zhai L, Zhang L, Yi M, Du B, Li S. A novel hybrid battery thermal management system with fins added on and between liquid cooling channels in composite phase change materials. Applied Thermal Engineering. 2022;207.

[9] Martin Philip Bendsøe, Kikuchi N. Generating optimal topologies in structural design using a homogenization method. Computer Methods in Applied Mechanics and Engineering. 1988;71:197-224.

[10] Marck G, Nemer M, Harion J-L. Topology Optimization of Heat and Mass Transfer Problems: Laminar Flow. Numerical Heat Transfer Part B-Fundamentals. 2013;63:508-39.

[11] Li Q, Steven GP, Querin OM, Xie YM. Shape and topology design for heat conduction by Evolutionary Structural Optimization. International Journal of Heat and Mass Transfer. 1999;42:3361-71.

[12] Asadpoure A, Tootkaboni M, Guest JK. Robust topology optimization of structures with uncertainties in stiffness - Application to truss structures. Computers & Structures. 2011;89:1131-41.

[13] Bruns TE. Topology optimization of convection-dominated, steady-state heat transfer problems. International Journal of Heat and Mass Transfer. 2007;50:2859-73.

[14] Zeng S, Kanargi B, Lee PS. Experimental and numerical investigation of a mini channel forced air heat sink designed by topology optimization. International Journal of Heat and Mass Transfer. 2018;121:663-79.

[15] An Z, Zhang C, Gao Z, Luo Y, Dong Y. Heat dissipation performance of hybrid lithium battery thermal management system using bionic nephrolepis micro-channel. Applied Thermal Engineering. 2022;217.

[16] Li S. Research on thermal management system of liquid-cooled battery based on bionic structure [Master]: Chongqing jiaotong University, Chongqing, China; 2022.