

EXPERIMENTAL EXPLORATION OF FINNED COOLING STRUCTURE FOR THE THERMAL MANAGEMENT OF LITHIUM BATTERIES WITH DIFFERENT DISCHARGE RATE AND MATERIALS

by

**Shixue WANG^{a,*}, Kaixiang LI^{a,b}, Ming GAO^a,
and Junyao WANG^b**

^a School of Mechanical Engineering, Tianjin University, Tianjin, China

^b MOE Key Laboratory of Efficient Utilization of Low and Medium Grade Energy,
Tianjin University, Tianjin, China

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Lithium-ion batteries in electric vehicles generate heat continuously, leading to high temperature of the battery packs and significant temperature differences between the battery cells, which eventually deteriorate the performance and lifespan of lithium-ion batteries. Therefore, a novel battery thermal management system that equipped the battery pack with fins was proposed and experimentally studied in this paper. The thermal behavior of lithium-ion batteries with different discharge rates and fin thicknesses was investigated. The results show that under natural-convection conditions, the addition of fins restricted the significant increase of the battery pack temperature and improved the uniformity of temperature distribution in the battery pack. Additionally, thicker fins satisfied the temperature requirements at higher discharge rates and greater discharge depths. Under condition of 2C discharge at 80% depth of discharge, compared to no clearance structure the 1 mm and 3 mm aluminum finned structure decreased the maximum temperature rise and the maximum temperature difference by 26.5%, 40.8%, and 9.5%, 33.3%, respectively. However, the trade-offs and optimization between the thermal load, weight, and volume increase caused by the addition of fins should be further investigated.

Key words: lithium-ion batteries pack, battery thermal management system, metal fin, natural-convection, lithium-ion battery safety

Introduction

Increasing energy crisis and environmental concern have accelerated development of electric vehicles (EV) recently. Lithium-ion batteries (LIB) are emerging as the most potential candidate for EV power batteries due to their superior characteristics [1]. However, LIB continue to generate heat during operation, resulting in high temperature of the battery pack and significant temperature difference between the cells, which affects their performance and lifespan [2-4]. Previous experiments have indicated that the best working temperature for LiFePO₄ batteries is between 18-45 °C [5]. Additionally, at 25 °C ambient temperature, the maximum temperature rise for batteries should not exceed 20 °C and the acceptable temperature difference between cells should be less than 10 °C [5].

* Corresponding author, e-mail: wangshixue_64@tju.edu.cn

Several studies have focused on the battery thermal management system (BTMS) as summarized in tab. 1. Wang *et al.* [6] and Dong and Baek [7] studied the thermal properties of battery packs using different battery pack arrangements and battery box structures. The simulation results showed that under certain conditions, battery pack arrangements and battery box structural optimization improved battery pack functionality under wider temperature ranges. Chang and Chen [8] performed for the thermal management system of power battery package containing 120 6 Ah nickel-hydrogen cells. Results show that the reliability and durability of battery and the volumetric specific power of battery pack are all enhanced by adjusting air mass-flow and duct. Jin and Wang [9] and Duan and Naterer [10] performed experiments and modeled the effect of phase change materials (PCM) on battery temperature change the results showed that latent heat of PCM capable of controlling battery temperature. Wei *et al.* [11] and Panchal *et al.* [12] employed thermal management of forced liquid cooling, and several design parameters are studied and analyzed. The results showed that higher coolant velocity and coolant plate thickness help in keeping the maximum temperature and temperature non-uniformity under control. Zou *et al.* [14] and Rao *et al.* [15] used heat pipe/fins and heat pipe/PCM system for battery cooling, and the applicability of heat pipe in thermal management system was proved. Al-Hallaj *et al.* [16] studied a plug-in hybrid VE, the battery pack heat load matching of the corresponding PCM and numerical analysis of the cooling system, the results showed that by adjusting the battery configuration and amount of PCM, the maximum temperature difference control was capable of keeping the battery pack within 1 °C. Additionally, the battery discharge capacity and cycle life were significantly increased. Wang *et al.* [17] and Park *et al.* [18] investigated battery performance applying flat micro-heat pipe array and radiator fins through simulation. They indicated that the set-up effectively solved heat dissipation and thermal storage problems of LIB.

Table 1. Summary of existing BTMS

Cooling method	Strength	Weakness	Complexity and cost	References
Forced air cooling	Applicable to all kinds of battery packs	low cooling efficiency when the ambient temperature rises	Medium	[6] [7] [8]
Liquid cooling	High cooling efficiency	Coolant may leak and cause short circuit	High	[11] [12] [13]
PCM	It has vast latent heat and the function of thermal storage	PCM will lose effect when it is completely melting	Medium	[9] [10] [19] [20] [21-22] [16]
Heat pipe	High thermal conductivity	It has a certain start-up temperature and requires a certain space for installation	Medium	[14] [15] [17] [18]
Finned cooling	Simple structure and no additional energy consumption	The compactness of battery pack are decreased	Low	[23] [24] [25] This study

Above all, various techniques such as forced air cooling, liquid circulation cooling, phase change material cooling, and heat pipe cooling have been applied to BTMS. However, these methods face the challenge of complicated structures as well as large investments. Specifically, the forced air cooling is high power consumption and cannot meet the requirement of battery thermal load at high discharge rate. The PCM has the function of thermal storage, but it will lose effect when it is completely melting and get poor performance under high temperature condition due to its low thermal conductivity; liquid circulation cooling needs complicated circulation loop and auxiliary pump system. Meanwhile, it has a risk of leakage and may cause short circuit of the battery pack. Heat pipe has quite high thermal conductivity. However, it requires a certain space for the evaporation side and condensing side. In addition, heat pipe must be installed in a certain angle for working fluid. Therefore, the heat pipe may not be suitable for a compact battery chamber. For now, most current research works focus on the design of complicated battery box structures by modifying circulating cooling fluid or composite PCM. Though these methods improve battery temperature performance, the resultant complicated structure, poor compactness, and high costs are major barriers.

The finned structure was proposed as an alternative cooling approach recently, which using natural-convection for heat dissipation with a simple structure as well as no extra power consumption. Chen *et al.* [23] experimentally studied and compared several heat-dissipating methods and heat-conducting mediums under similar heat load conditions and noted that finned heat dissipation and forced convection ($v = 2 \text{ m/s}$) are basically consistent with the maximum temperature rise and the maximum temperature difference of the battery pack. Mohammadian and Zhang [24] used pin-fin heat sinks for LIB module. The 3-D transient thermal analysis showed that the pin fins are in favor of decreasing the bulk temperature and improving the temperature uniformity. Kim and White [25] studied different materials such as copper, copper beryllium, silver, and sterling silver as heat-fin materials by using a 2-D thermal coupling model of NI-MH battery. The fin geometry (thickness and height) and spacing were tested and yielded an acceptable temperature gradient of the battery pack. He [26] proposed that the reasonable fin height of aluminum fin radiators should be in the range of 50-60 mm, at heat flux density of 1000 W/m^2 .

However, research on finned BTMS is still at the early stage. Until now, most of the studies are numerical simulation without sufficient experimental verification. In this study, the rectangular fins, which are commonly used in heat exchangers, are proposed to be applied in the BTMS. The metal plate between each cell also works as heat transfer medium to assist maintaining a uniform surface temperature for cells. A total of thirteen different structures were designed and the effects of depth of discharge (DOD), discharge rate, thickness, and material of fins on the battery thermal behavior were experimental studied under natural-convection conditions, and it provides a reference for the further design of BTMS.

Methodology

Experimental system

The experimental set-up is shown in fig. 1. The battery test equipment consisted of a lithium battery test system with maximum charge and discharge voltage of 100 V, and maximum charge and discharge current of 200 A. The test system was capable of controlling the battery charge and discharge processes, col-

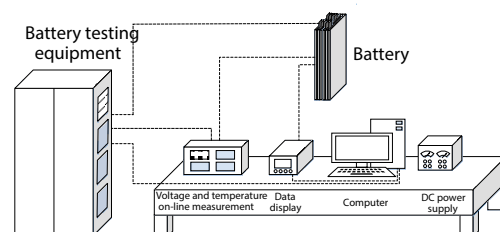


Figure 1. Physical model of the experimental system

lecting and recording electric current, pack voltage, and cell voltage using test control software installed on the computer. The GP10 digital display device (GP10, Yokogawa Electric Corporation, Tokyo, Japan) was used to collect and record temperature parameters.

Battery packing LiFePO₄ battery (7.7 mm in height, 180 mm in width, 200 mm in length), with nominal voltage of 3.2 V and rated capacity of 22 Ah was used to investigate thermal behavior. Three configurations were experimentally studied:

- no clearance,
- equal clearance, and
- added fins.

The battery pack consisted of six cell units connected in series, as shown in fig. 2. The positive current collector, indicated in grey, was made of an aluminum foil while the negative

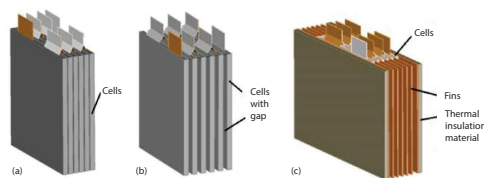


Figure 2. Different structures of battery pack; (a) no clearance, (b) equal clearance, and (c) metal fins

current collector, indicated in brown, was made of a copper foil. The height of the fins was set at 60 mm based on simulation results [26], while the designed metal plate was 300 mm in width and 200 mm in length. The middle line along the length of the metal plate was designed to align with middle line along the width of the battery cells. Thus, 60 mm extended from the metal plates and were regarded as radiating fins.

This study focused on the temperature behavior during the discharge process when the battery pack was under natural-convection conditions, ensuring the absence of wind currents during the experimental process. The discharge rates were set at 0.5C, 1C, 1.5C, 2C, 2.5C, and 3C for all three battery-pack structures (1C = 22 A, 2C = 44 A, *et al.*). The discharge cut-off voltage was set at 2 V, and the ambient temperature variation range was 25 ± 1 °C, with fluctuation less than 2 °C. Typical CC-CV charging mode was employed during the experimentation. The battery was charged with 1C constant current till the voltage reaching 3.65 V when the battery went into constant voltage charge, and the cutoff current was set as 0.05 °C. After the charging process, batteries were placed to cool to the ambient temperature. Thus, chemical reactions inside the battery halted. When temperature difference of each measuring point (in next section) returned to within 0.2 °C, the next discharge cycle was initiated. For battery packs equipped with metal fins, tightening torque of each point at the clamping batteries and fins was maintain consistent to avoid different pressures, which can affect the measurement of thermal characteristics.

Thermocouple arrangement

Battery surface temperatures were measured using *T*-type thermocouples with less than 0.1 °C temperature difference between the measured and calibrated values. Totally, 28 sets of thermocouples were fixed on the battery surface using ultrathin adhesive tape made of red copper. The attachment points of the thermocouples are shown in fig. 3. It should be noted that the setting of thermocouple would not lead to clearance between the contact surface of cells and fin structures because of the negligible diameter of the thermocouple ($\varnothing = 0.25$ mm) as well as the excellent ductility of the aluminum composite membrane. The paired numbers in fig. 3(a) indicate bilaterally symmetrical thermocouples fixed on the same battery surface. Figure 3(b) shows the measuring points on each battery. During the discharge process, the temperature of the upper part of the battery cell was higher than the lower part due to its proximity to the tabs. Thus, more thermocouples were arranged on the upper area. Furthermore, the thermocouples

were fixed on a single surface due to battery structure symmetry and temperature distribution. An additional thermocouple was used to measure the ambient temperature. In this study, the highest and lowest temperatures, T_h and T_l , of the battery pack represented the highest and lowest temperatures measured by the 28 sets of thermocouples, respectively. The maximum temperature increase, T_{inc} , was defined as the temperature difference between the highest temperature of the battery pack and the initial battery temperature. The temperature difference between the highest and lowest temperatures of the battery pack was defined as the maximum temperature difference, ΔT_{max} .

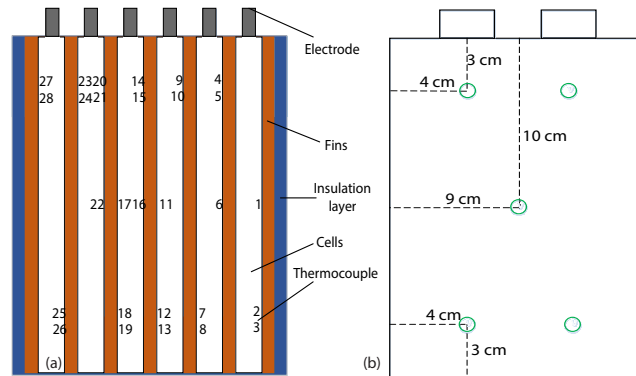


Figure 3. Thermocouple lay-out on the battery pack and surface; (a) thermocouple lay-out on battery pack, (b) thermocouple lay-out

Results and discussion

Basic thermal characteristics of battery during discharge process

Highest and lowest temperature points

Due to different heat generation rates in different parts of the battery, temperatures varied at each measuring point during the discharge process. In order to lower the highest temperature and reduce the temperature difference inside the battery pack, positioning T_h and T_l points correctly for each battery configuration was necessary.

Location change of the T_h and T_l points over time in the battery pack configurations of no clearance is shown in tab. 2. The surface temperatures were uniform at the beginning of discharge. However, the temperature of different measuring points began to vary during the process of discharge and the locations of T_h and T_l tended to be approximately stable. The T_h area was in the upper part, at thermocouple measuring points 15 for no clearance, which is at the bottom of the electrode of the internal cells, because of high current density and poor heat convection at this area. The T_l area was in the lower part, at thermocouple measuring points 2, due to the low current density and good heat convection.

Table 2. Change of T_h and T_l location on the battery pack over time

Time [s]		0	300	600	900	1200	1500	1800
Temperature of no clearance [°C]	T_h	8	15	15	15	15	15	15
	T_l	5	2	2	2	2	2	2

Effect of depth of discharge on battery thermal characteristics

Figure 4(a) shows the battery internal resistance, R , profile with the change in DOD following the hybrid pulse power characteristic test for the no clearance structure. The discharge capacity of the tested battery was 21.1 Ah, Therefore, the maximum DOD was 96%. It is clear that R increased with the increase in heat generation rate, leading to rising in temperature. When the DOD was over 80 %, there was significant growth in heat generation during the later

stage of the constant discharge process because of the sharp increase of R , which may present a safety hazard. Figure 4(b) demonstrates the influence of DOD on the voltage of battery pack, U , with 1C, 2C, and 3C discharge rates using the no clearance structure. For each discharge rate, the pack voltage collapsed at the starting moment due to polarization effect when the electric current changed suddenly. Subsequently, the battery began discharging at a stable voltage reaching the voltage platform. Polarization phenomenon was more obvious with higher discharge rate and lower voltage platform. When the DOD was over 80%, the sharp increase of R would cause significant increase of the irreversible heat production rate. As a consequence, U showed considerable decline trend, and the output power decreased as well. The phenomenon will severely affect the performance of the battery pack. Therefore, a highly efficient BTMS is necessary during the later stage of the discharge process. As highlighted in section *Introduction*, the battery maximum temperature rise should not exceed 20 °C and the acceptable temperature difference between cells should be less than 10 °C. Therefore, fig. 5 indicates that the structure of no clearance battery pack was not capable of meeting the requirements of maximum temperature rise and temperature difference at 2C or higher discharge rates.

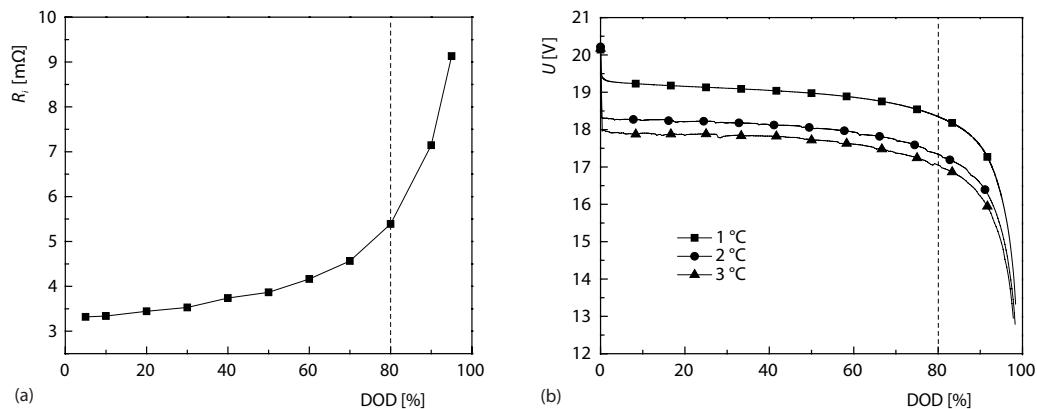


Figure 4. Influence of DOD on battery internal resistance and pack voltage of no clearance structure; (a) resistance changes with DOD, (b) battery voltage changes with DOD

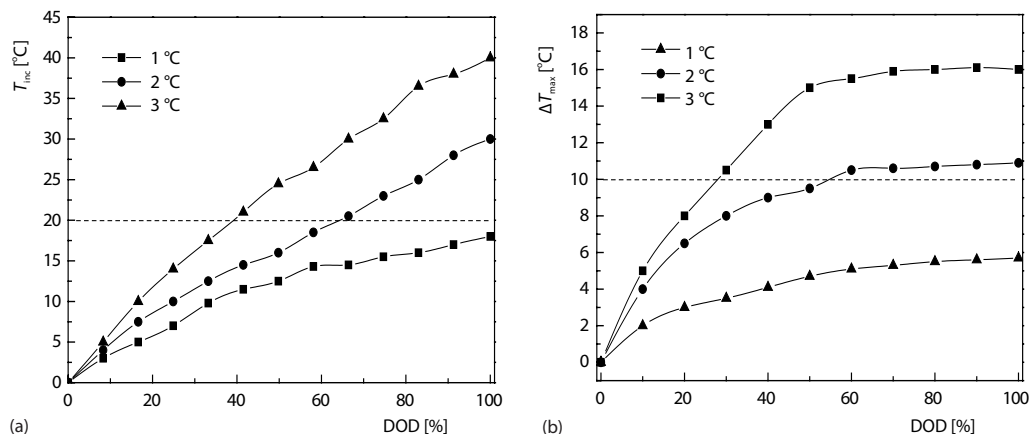


Figure 5. Influence of DOD on T_{inc} and ΔT_{max} in of no clearance structure

Effect of cell clearance on battery thermal characteristics

Six cells were connected in series at equal distances of 0 mm (no clearance), 2 mm, and 4 mm as shown in figs. 2(a) and 2(b). The variations in T_{inc} and ΔT_{max} with respect to the discharge rate are demonstrated in fig. 6. It is clearly that the 2 mm space was too small for natural convection, especially when the discharge rate and temperature were low. At such conditions, the small space had little effect on battery cooling. In addition, the air in the small space increased heat resistance between the battery cells. Thus, T_{inc} of this configuration was slightly higher than the no clearance configuration. However, when the discharge rate and temperature were high, natural convection was enforced that T_{inc} was almost the same as the no clearance configuration.

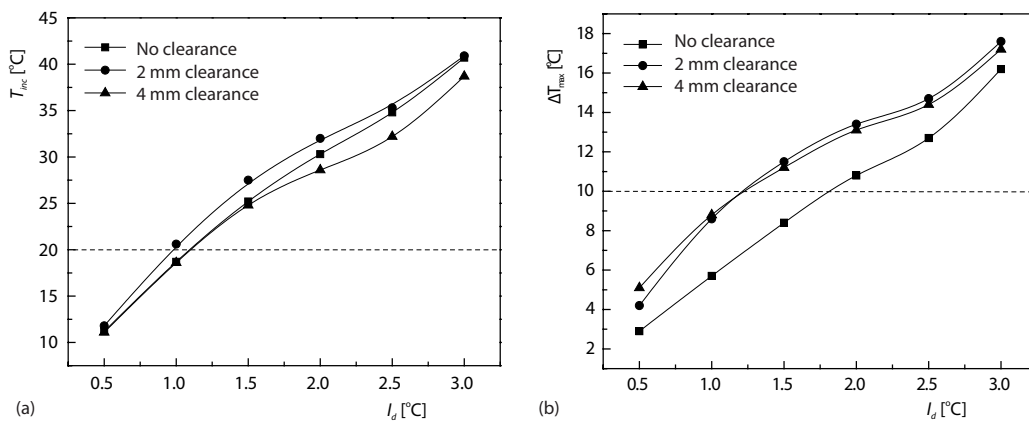


Figure 6. Influence of discharge rate on T_{inc} and ΔT_{max} for cell with clearance

When the battery space was 4 mm, T_{inc} was lower than the 2 mm space configuration at all discharge rates, as natural-convection was stronger and heat dissipation capacity is enhanced. In fact, under low discharge rate, T_{inc} of the 4 mm configuration was almost the same as the no clearance structure and lower than that of the 2 mm structure, while under high discharge rate, the T_{inc} of 4 mm structure was 2-3 °C lower than the no clearance configuration, which indicated that an increase in cell space can reduce T_{inc} .

As shown in fig. 6(b), the temperature uniformity performances of the 2 mm and 4 mm space structures were weaker compared to the no clearance structure indicated by the ΔT_{max} . The main reason is that heat was transferred efficiently from the internal to the external cells in the no clearance structure, while the heat of the internal cells was barely transferred to the external cells in the clearance structure, leading to high ΔT_{max} . In addition, the ΔT_{max} for 2 mm and 4 mm space structures were similar, which indicated that slightly enlarged space may increase ΔT_{max} to a limited extent.

It is indicated that increasing the space slightly could not achieve reduction in both T_{inc} and ΔT_{max} . Furthermore, increasing the space further can result in larger volume and poor structure of the battery pack. Thus, other advanced methods are necessary to enhance the battery heat dissipation.

The finned BTMS

Effect of finned structure on battery thermal characteristics

Figure 7(a) shows the T_{inc} profile with respect to DOD when the discharge rate at 2C for no clearance structure, 1 mm thickness aluminum fins, and 3 mm thickness aluminum fins.

It is clearly that T_{inc} increased with DOD during 2C discharge rates for all structures. At the early stage, the temperature difference between the battery pack and environment was low, thus most heat generated by the battery was used for temperature increase. During the middle stage, the temperature difference increased while the heat generation rate remained constant, thus the temperature registered slow increase rate. At the later stage, heat generation rate increased sharply due to sharp increase in R while the heat loss rate was almost same. Therefore, sharp temperature increase, higher than 20 °C was recorded. The T_{inc} of the finned structure was lower than the structure without fins at the same DOD. Additionally, we noted that T_{inc} decreased with increase in the thickness of the fins. In details, the thicker finned structure could achieve larger DOD before reach the limit of temperature rise implying that more electric power can be discharged safely. For example, during 2C discharge to 80% DOD, the T_{inc} of the battery pack without fin was 24.5 °C, which was above the 20 °C standard. When 1 mm and 3 mm thick fins were added, the T_{inc} was 18 °C and 14.5 °C, which corresponded to 26.5% and 40.8% decrease, respectively, compared to the battery pack without fin. During 2C discharge, corresponding DOD for no clearance and fin thicknesses of 1 mm, and 3 mm, were 65%, 85%, and 100%, respectively when the T_{inc} of battery pack increased up to 20 °C.

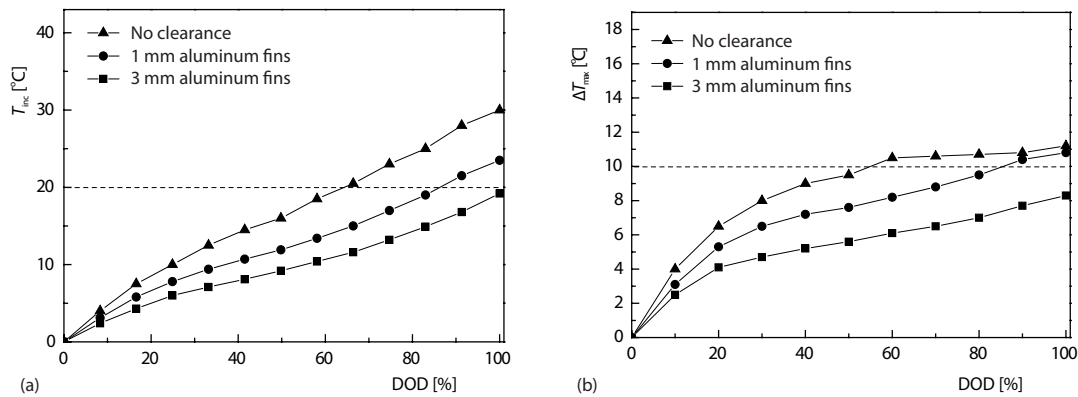


Figure 7. Influence of DOD on T_{inc} and ΔT_{max} of battery pack with aluminum fins

Figure 7(b) indicates the ΔT_{max} trend with change in DOD at 2C discharge rates for structure of no clearance and finned structures. As for the structure of no clearance, ΔT_{max} increased initially and then change to be steady as the DOD was over 80%. The main reason is that at the later stage, battery heat production rate was accelerated, the intensity of natural-convection was weak, and a large amount of heat was produced but not dispersed in time. The battery pack can be regarded as a whole pack with high temperature at this stage. In addition, ΔT_{max} in the finned structure was quite smaller than the structure without fins. On the one hand, ΔT_{max} was smaller for the battery pack with thicker fin with the same DOD. For example, at 2C discharge to DOD 50%, the ΔT_{max} of the battery pack of no clearance and with fin thicknesses of 1 mm, and 3 mm was 10.5 °C, 9.5 °C, and 7.1 °C, respectively. The 1 mm and 3 mm fin lifting effect of temperature equalization by 9.5% and 33.3%. This illustrates that the thicker fin can achieve greater DOD and meets the allowable maximum temperature difference conditions simultaneously. On the other hand, the allowable DOD was larger for the thicker fin structure at the same DOD. For instance, in 2C discharge for no clearance and fin thicknesses of 1 mm, and 3 mm, corresponding DOD were 55%, 85%, and 100%, respectively, when the ΔT_{max} of the battery pack went up to 10 °C. Thus, metal fins can effectively decrease T_{inc} and ΔT_{max} as well as extend the DOD and working duration at the optimum temperature.

Effect of fin thickness on battery thermal characteristics

Figure 8(a) shows the T_{inc} profile of finned structures with variation in discharge rate under natural convention conditions. The results show that the aluminum fins favored a decrease in T_{inc} . Additionally, at the same discharge rate, T_{inc} was smaller when the fins were thicker. All the four thicknesses of aluminum fins met requirements of maximum temperature rise at discharge rate under 1.5C. When the fin thickness was 4 mm, at 2.5C discharge, the T_{inc} was slightly higher than 20 °C, which is regarded as qualified at 2.5C discharging.

Figure 8(b) shows the trend of ΔT_{max} for finned structures with respect to the discharge rate. The ΔT_{max} exhibited an increasing trend when the discharge rate increased. Compared to fig. 7(b), the structure with fins effectively improved the temperature uniformity of the battery pack and battery thermal performance improved proportionally with the thickness of fins. The ΔT_{max} of the battery pack was not higher than 10 °C at any fin thickness, when the discharge rate was 1.5C or lower. The ΔT_{max} was slightly above 10 °C when the battery pack had 4 mm aluminum fins in the 3C discharge, which is qualified at 3C discharging.

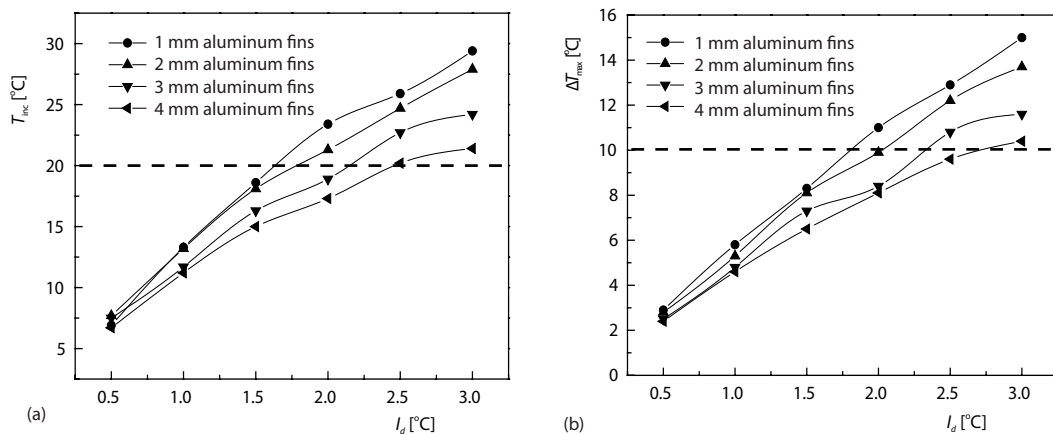


Figure 8. Effect of discharge rate on T_{inc} and ΔT_{max} of the battery pack with aluminum fins

It should be noted that limitations related to both T_{inc} and ΔT_{max} need to be satisfied. The 2-D graphs of T_{inc} and ΔT_{max} are shown in fig. 9. When the point was located at the bottom left rectangle area, both T_{inc} and ΔT_{max} could satisfy the requirements. As shown in fig. 9, the points moved to the upper left side when the discharge rate increased, thus fewer structures could meet the BTMS requirement. Moreover, required fin thickness was increasing. At 2C or lower discharge rates, 3 mm aluminum fins could meet requirements of BTMS, while at 2.5C discharge conditions, only when the 4 mm aluminum fin is assembled, both T_{inc} and ΔT_{max} was able to meet the requirement.

The T_{inc} and ΔT_{max} profiles for different structures at ambient temperature of 25 °C are shown in fig. 10. Both T_{inc} and ΔT_{max} showed decreasing trends with increase in the thickness of fins. For instance, under 3C discharge the structure of no clearance (indicated as 0 mm in fig. 10) and with fin thicknesses of 1 mm, 2 mm, 3 mm, and 4 mm, T_{inc} was 40.5 °C, 29.4 °C, 27.9 °C, 24.2 °C, and 21.4 °C, respectively. Correspondingly, ΔT_{max} was 16.1 °C, 15.0 °C, 13.7 °C, 11.6 °C, and 10.4 °C, respectively, at the end of discharge. As shown in fig. 10(a), T_{inc} of 1 mm thickness fin was markedly smaller than the structure without fins. However, when the thickness of fins was in the range of 1 mm to 4 mm, the decline in T_{inc} was not obvious. The T_{max} exhibited continuous decline with increase in fin thickness. This decline was particularly

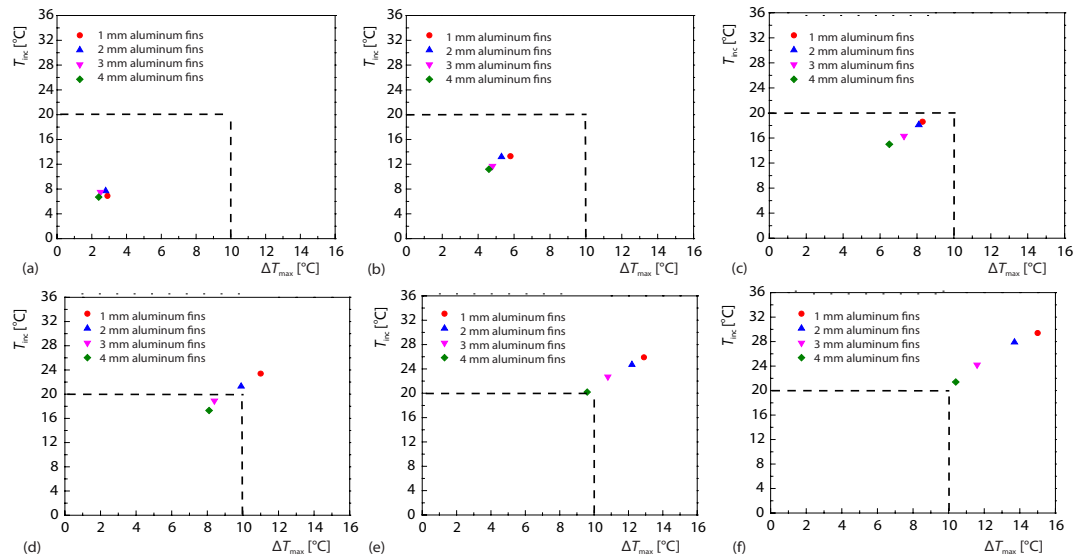


Figure 9. Temperature performance for T_{\max} and ΔT_{\max} of the battery pack with aluminum fins; (a) 0.5C discharge, (b) 1C discharge, (c) 1.5C discharge, (d) 2C discharge, (e) 2.5C discharge, (f) 3C discharge

obvious at high discharge rates and thicker fin assembly. It can be concluded that thicker fins help to export heat from the high temperature region and transfer it to the air by convection and the thermal behavior of the battery packs can be improved by adding aluminum fins.

Effect of fin material on battery thermal characteristics

Figure 11 shows the temperature responses of aluminum and copper fins at 2C discharge rate. Although the temperature response trends for all four structures were similar, the performance of copper fin structures was better than the aluminum fin structures. It should be noted that the curve of T_{\max} and ΔT_{\max} for the 3 mm aluminum fin and 1 mm copper fin structure were almost overlapping, which indicated that they have the similar thermal management performance. However, in such condition, the required volume and mass of aluminum fin were approximately three times as that of copper fins. Therefore, the total mass and volume ratio between the aluminum and copper fin structured battery pack were up to 1.05:1 and 1.12:1.

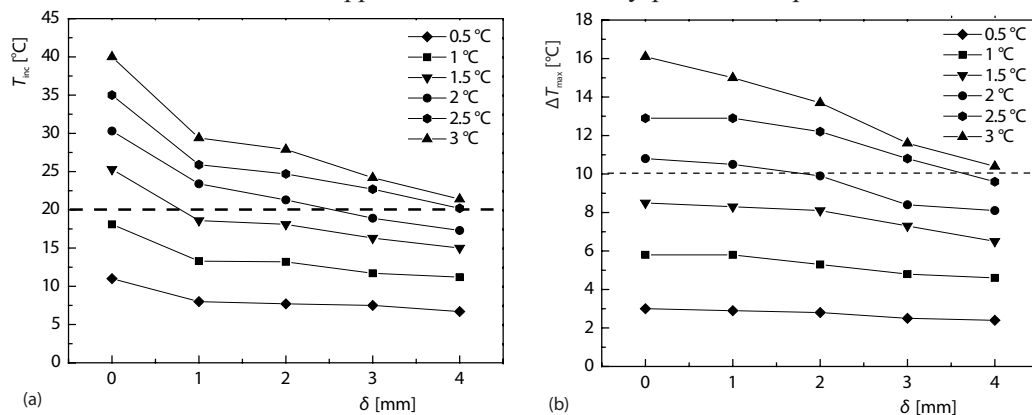


Figure 10. Influence of fin thickness on T_{\max} and ΔT_{\max} of the battery pack with aluminum fins

Consequently, 1 mm copper fin was considered as optimum selection after taking total volume and total mass into consideration. It is noted that the heat conduction capacity of the finned battery pack is the critical factor dominating the heat transfer effect while the convective heat resistance between the fin and the environment is less important. As the aforementioned, add fin and increase its thickness, thermal management effect can be improved under the condition of natural-convection. On the other hand, the selection of 60 mm fin height can meet the requirements of heat dissipation under various working conditions.

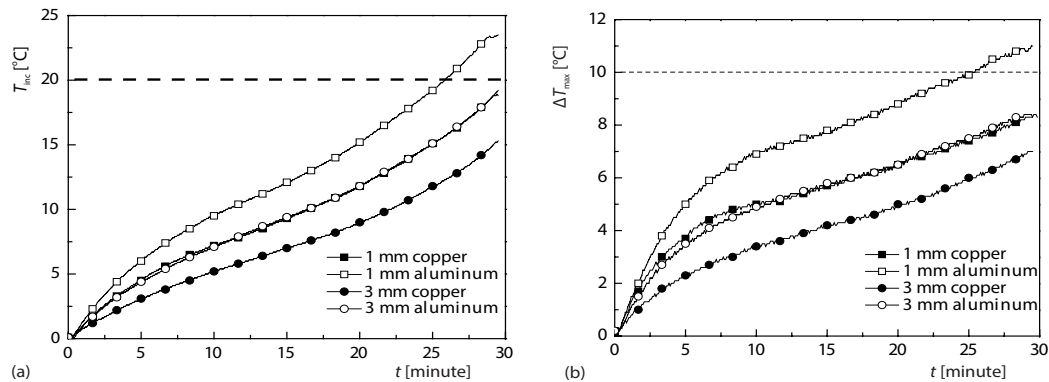


Figure 11. Influence of discharge time on T_{inc} and ΔT_{max} of the battery pack with aluminum and copper fins

Figure 12 shows T_{inc} and ΔT_{max} performance using different fin materials at discharge rates of 2C and 3C. As evident, when the thickness of aluminum fins and copper fins were the same, copper fin structure performed better under the same discharge rate due to the higher heat transfer rate of copper. This is mainly because that the copper's coefficient of thermal conductivity is 1.69 times higher than aluminum, $\lambda_{cu} = 398$ W/mK, $\lambda_{al} = 236$ W/mK. As the heat dissipation efficiency of fin increased with the thermal conductivity of fin material, the heat dissipation effect of the copper fin was better than the aluminum fin at the same thickness when they had the same heat transfer area. Overall, experiments show that 1-4 mm copper and aluminum fins can meet requirements of T_{inc} and ΔT_{max} at 1.5C or lower discharge. For 3C discharge conditions, 3 mm or higher thickness copper fins were needed.

However, it is worth noting that, in battery pack structure consisting of six cells connected in series, adding fins increases the total mass of the battery pack considerably. In fact, the addition of seven pieces of 1 mm copper fins would result in increasing of total battery pack mass by 95.8%, which is nearly double compared to the structure without fins. While

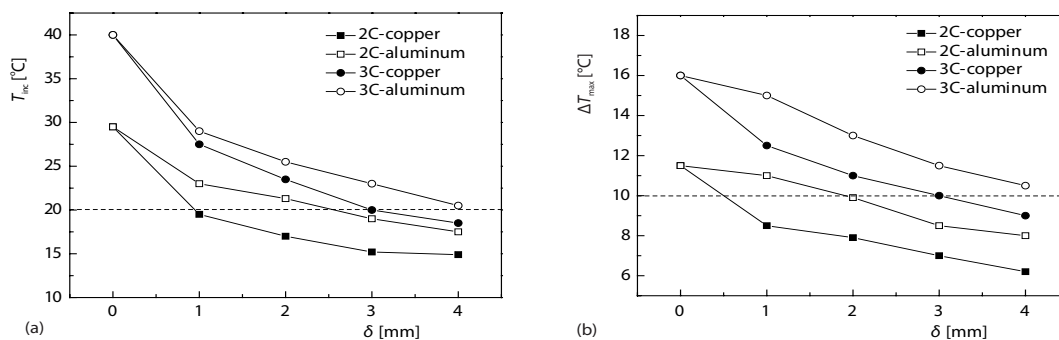


Figure 12. Influence of fin thickness on T_{inc} and ΔT_{max} with fins of different materials

addition of seven pieces of 1 mm aluminum fins increased the battery pack mass only by 29.1%. Additionally, as the fin extends outside the battery, the added fins also tend to increase the volume of the battery pack. Thus, addition of seven pieces of 1 mm copper or aluminum fins increased the volume of the battery pack by 91.9%, and then every 1mm thickness increase on fin material led to 15.2% increase of total battery volume correspondingly. In general, the mass issue is more severe than that of the volume, therefore, to guarantee better thermal management, mass factors should take precedence over the volume when selecting fin material, and the material that increases less total quality of battery pack is preferable. For practical engineering application, several other factors should be taken into account, and trade-offs between thermal behavior, volume of battery compartment, lay-out arrangement, and weight of fins need to be evaluated.

Conclusions

The T_{inc} and ΔT_{max} are two important criteria to evaluate the thermal management effect of battery packs. This study explores an alternative BTMS method by using finned structures under natural-convection conditions. The thermal behavior of laminated lithium batteries with and without clearance were measured. Effects of clearance between battery cells, the fin thickness and the fin material on the battery pack thermal characteristics were experimental investigated. Based on the presented results, the main conclusions were drawn.

- For laminated lithium battery, during discharge process the highest temperature area was located at the upper side of the battery near the positive electrode. Lowest temperature area was located in the bottom of the battery, away from the positive electrode. The T_{inc} and ΔT_{max} could not be decreased solely by increasing the space between the battery cells.
- The T_{inc} and ΔT_{max} increased with increase in discharge rate and the vast majority of DOD. Additionally, T_{inc} and ΔT_{max} have declining trends when the thickness of fins decreased under different discharge rates. Thus, thermal management was achievable. Under condition of 2C discharge at 80% DOD, compared to no clearance structure the 1 mm and 3 mm aluminum finned structure decreased the maximum temperature rise and the maximum temperature difference by 26.5%, 40.8% and 9.5%, 33.3%, respectively. The T_{inc} and ΔT_{max} increased with the increase in discharge rate, which indicates that the thermal management was more difficult when the discharge rate was high. The battery pack with thicker fins could meet the requirement of thermal management under higher discharge rate.
- Fins made of different materials have different effects on T_{inc} and ΔT_{max} . Under condition of 2C discharge, the 3 mm aluminum fin and 1 mm copper fin structure have the similar thermal management performance. The material with higher heat conductivity coefficient increased heat dissipation more efficiently.

Further study should focus on the design of EV battery compartment for fin structure. In addition, research on the performance of fins with different shapes, as well as the feasibility of BTMS, which combines the fin structure and other available method (e. g., PCM) should be further investigated.

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