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Performance Analysis of a Wet Pad Assisted Air-cooled Battery Thermal Management System

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ABSTRACT

Air-cooled battery thermal management technology is well developed and inexpensive, but the small convection coefficient of air limits the heat dissipation capability of the system. In this paper, a wet pad is applied to pre-cool air before it passing through the battery pack. Fluent software is used to establish a model of the lithium-ion battery pack to simulate the surface temperature of the battery. Comparative study on the temperature distribution of the same battery pack with and without the wet pad is conducted under various ambient conditions and air velocity. Simulation results show that better cooling performance of the wet pad can be obtained at higher and arid ambient conditions. Increased air velocity brings in slightly reduced cooling efficiency of the wet pad. But it can enhance the heat transfer among airflow and the battery pack. Overall, thermal performance of the proposed wet pad assisted air-cooled battery thermal management system is improved compared to a traditional one.

Keywords: Electric vehicles, Battery thermal management, Forced air cooling, Direct evaporative cooling

NONMENCLATURE

Abbreviations	
BTMS	Battery thermal management system
DEC	Direct evaporative cooler
RH	Relative humidity
T_{max}	Maximum temperature of the battery pack
ΔT	Maximum temperature difference inside the battery pack
Symbols	
A	Heat and mass transfer area (m^2)
C_p	Specific heat capacity (J/(kg·K))
h_c	Convective heat transfer coefficient (W/(m^2·K))
h_m	Mass transfer coefficient (m/s)
I	Cell current (A)
k_a	thermal conductivity(W/(m·K))
L	Characteristic length (m)
l_{gap}	Pad thickness (m)
m_a	Mass flow rate of incoming air (kg/s)
Nu	Nusselt number
Pr	Prandtl number
q	Heat generation rate per unit volume (W)
Re	Reynolds number
T	absolute temperature (K)
$T_{a,in}$	Inlet dry-bulb temperature (K)
$T_{a,out}$	Outlet dry-bulb temperature (K)
$T_{a,wb}$	Inlet air wet-bulb temperature (K)
t	Discharge time(s)
U	Working voltage (V)
U_0	Open-circuit voltage(V)
V	Volume (m^3)
$\omega_{a,in}$	Inlet moisture content (g/kg)
$\omega_{a,out}$	Outlet moisture content (g/kg)
$\omega_{a,wb}$	Inlet air moisture content (g/kg)
λ_r	Normal thermal conductivity (W/(m·K))
λ_ϑ	Radial thermal conductivity (W/(m·K))
λ_z	Axial thermal conductivity (W/(m·K))
η	cooling efficiency
ρ	Density (kg/m^3)

1. INTRODUCTION

Lithium-ion batteries have been widely used to drive electric vehicles and hybrid electric vehicles owing to their low self-discharge rate, high energy density, and high stability. Heat generated during the work of batteries may accumulate inside the battery pack and cause the local high temperature, threaten the safety of

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batteries. Apart from safety concern, the thermal performance and capacity of the battery pack are also highly depended on the operating temperature, which optimum range is usually between 20 °C and 40 °C [1]. The maximum temperature difference within the entire battery pack should also be controlled to less than 5 °C [2]. Therefore, proper battery thermal manage system (BTMS) is required.

Air cooling system stands out among them due to its structure simplicity and cost-effective. However, the cooling capacity of air cooling BTMS is limited owing to the low thermal conductivity and low heat capacity of air. Therefore, the structure of traditional air cooling BTMS should be improved to handle higher energy dissipation due to the increasing demanding of energy density, cycle life and high current of lithium-ion batteries.

Mi et al. [3] have investigated the thermal performance of the battery pack installed with cooling fin. Simulation results show that thermal performance of the battery pack improves with the size of the cooling fin. Evaporative cooling provides an alternative pre-cooling for battery pack owing to its ability to dissipate high heat flux via water evaporation [4]. Youssef et al. [5] represents the first attempt to analyze the performance of jute fiber as a cooling medium in BTMS. Further experiments were carried out on the water evaporation system, where a wet pad is put before the battery pack [6]. Comprehensive studies showed that a low relative humidity (RH) is preferred for better cooling effects and reciprocating air flow can improve the temperature uniformity among batteries. Other factors, such as ambient temperature and air velocity, are not discussed yet.

Compared to direct water spraying in the air flow chamber, the use of a wet pad can greatly increase the contact area between water and the surrounding air, forming a direct evaporator. In this paper, a comprehensive influence factors of the wet pad assisted air cooling BTMS are considered to discover how ambient conditions and air velocity affect the thermal performance of both the direct evaporator and the battery pack.

2. PAPER STRUCTURE

2.1 Modeling of the direct evaporative cooler (DEC)

The DEC model refers to a previous study by G. Heidarinejad et al. [7] which has been experimentally validated. By assuming the water in the DEC can reach the wet-bulb temperature of the inlet air, the governing equations of heat and mass conservation are given in Eq.(1) and (2). Therefore, the outlet temperature and humidity of the air pass through a DEC can be easily determined.

$$\frac{T_{a,out}-T_{a,wb}}{T_{a,in}-T_{a,wb}}=exp\left(-\frac{h_c A}{m_a c_{p,a}}\right) \tag{1}$$

$$\frac{\omega_{a,out}-\omega_{a,wb}}{\omega_{a,in}-\omega_{a,wb}}=exp\left(-\frac{h_m A}{m_a c_{p,a}}\right) \tag{2}$$

where, m_a is the mass flow rate of incoming air, kg/s; A is the heat and mass transfer area of a DEC, m^2; $T_{a,in}$ and $T_{a,out}$ refer to the inlet and outlet dry-bulb temperature of a DEC, ℃; $\omega_{a,in}$ and $\omega_{a,out}$ are the inlet and outlet moisture content of a DEC, g/kg; $T_{a,wb}$ and $\omega_{a,wb}$ are the wet-bulb temperature and moisture content of inlet air; h_c is the convective heat transfer coefficient calculated from Nusselt number ($\mathrm{Nu} = h_c L/k_a$) determined by an empirical formula of $0.1\left(L/l_{gap}\right)^{0.12} Re^{0.8} Pr^{1/3}$. h_m is the mass transfer coefficient by assuming Lewis number is 1.

2.2 Thermal modeling of the battery pack

The battery pack consists of 12 cylindrical lithium-ion powered batteries, as shown in Fig. 1 The size of each battery cell is 65 mm × 18 mm (height × diameter), with a gap of 4 mm between each battery cell.

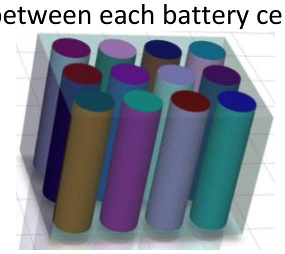


Fig. 1. Schematic diagram of the battery pack

Although the battery is a volume heat source, it is simplified to a surface heat source in order to decrease the number of grids and reduce the computational time. Based on the above simplification of the battery model, the control equation for the battery heating process is expressed in the following way

$$\rho C_p \frac{\partial T}{\partial t} = \lambda_r\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}\right)+\lambda_\theta \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\lambda_z \frac{\partial^2 T}{\partial \theta^2}+q \tag{3}$$

Where λ_r, λ_ϑ, λ_z are the thermal conductivity of the battery in the normal, radial and axial directions (W/(m·K)), ρ is battery density (kg/m^3), C_p is battery specific heat capacity (J/(kg·K)), q is the heat generation rate per unit volume (W).

In order to estimate the heat generation rate, the theoretical calculation model proposed by Bernardi was used [8]:

$$q=\frac{I}{V}\left[\left(U_o-U\right)-T\frac{\partial U_o}{\partial T}\right] \tag{4}$$

Where V is battery volume (m^3). U_0, U and I is open-circuit voltage(V), working voltage (V) and cell current (A), respectively. T is absolute temperature (K).

Table 1 Specification parameter table of lithium-ion battery

Parameter	Value
Size/mm	65 × 18
Nominal capacity/Ah	2.2
Density/kg/m^3	2722
Specific heat capacity/J/(kg·K)	970
Thermal conduction/W/(m·K) λ_r	2.6
λ_ϑ	2.6
λ_z	28

2.3 Test conditions

Three factors including the ambient dry-bulb temperature, RH, and air velocity are considered. In each case, the thermal performance of the battery pack is simulated with and in absence of the wet pad, respectively. Two indicators are used to assess the thermal performance of the battery pack under various conditions, namely, the maximum temperature of the battery pack (T_{max}) and the maximum temperature difference (ΔT) inside the battery pack.

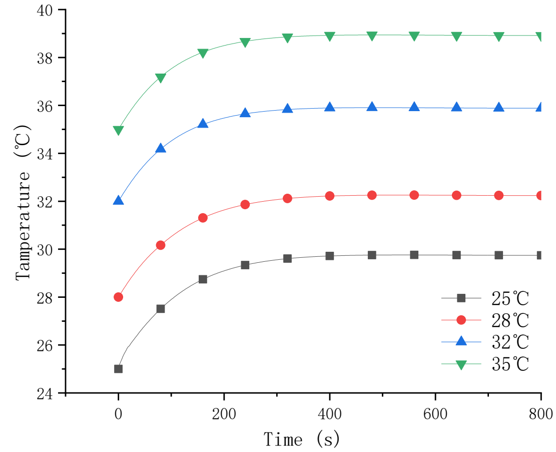
Table 2 Test conditions

Case number	Ambient dry-bulb temperature (°C)	RH (%)	Air velocity (m/s)	Charging rate
1	25-35	50	3	2C
2	25	40-70	3	2C
3	25	50	0.5-4	2C

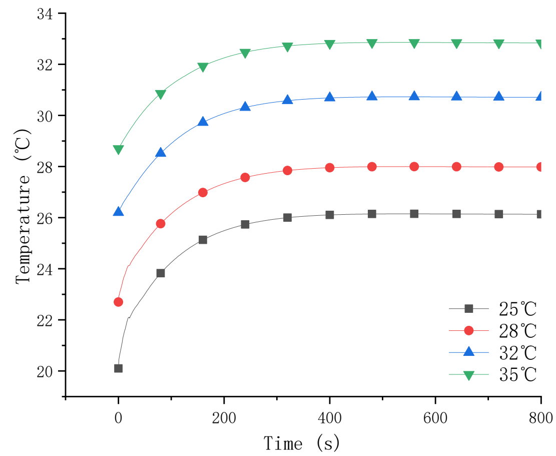
2.4 Results and discussion

2.4.1 Effect of ambient air dry-bulb temperature

Fig. 2 shows the maximum temperature evolution of the battery pack in case 1. As shown in Fig. 2 (a), surface temperature of the battery increases under tradition dry-cooling condition, and reaches steady state at around 400s. When it increases form 25 °C to 35 °C, the stabilized maximum temperature evolution of the battery pack ranges from 29.7°C to 38.9°C. If the ambient temperature is further increased, T_{max} will continue increasing, which may reach the threaten level of 40 °C. In Fig. 2 (b), owing to the pre-cooling effect of the wet pad, the inlet temperature to the battery pack drops by a large margin (4.9°C to 6.2 °C), ranging from 20.1 °C to 28.8 °C. Larger temperature drop can be obtained under higher ambient dry-bulb temperature at a constant ambient RH owing to higher evaporative cooling efficiency of the wet pad at high temperature. The convective heat transfer is conspicuously enhanced and the thermal performance of battery pack gets improved. At the end of charging, the T_{max} are 3.6 °C to 6.1 °C cooler than that of BTMS under traditional dry condition. It indicates that the application of the wet pad can help to reduce the inlet temperature of the battery pack and confine the maximum temperature evolution. It is more capable to scorching weather compared to traditional dry cooling system.



(a)



(b)

Fig. 2. T_{max} of the battery pack in case 1 (a) traditional dry-cooling (b) with wet pad

Apart from temperature rising, the temperature uniformity of the Li-ion battery pack is also a very crucial criterion. Fig. 3 presents the maximum ΔT of case 1. As shown in Fig. 3 (a), larger temperature difference of battery pack can be observed at lower ambient temperature. Similar trend of ΔT are obtained by the wet pad assisted BTMS, as shown in Fig. 3 (b). It rises and then stabilizes at around 4.1°C to 2.2°C, which is 1.7°C to 0.3°C higher than that of dry-cooling condition, when ambient air temperature increasing from 25 °C to 35 °C. It can be concluded that the application of the wet pad can confine the inlet temperature to the battery pack as well as T_{max} at the cost of slightly higher ΔT.

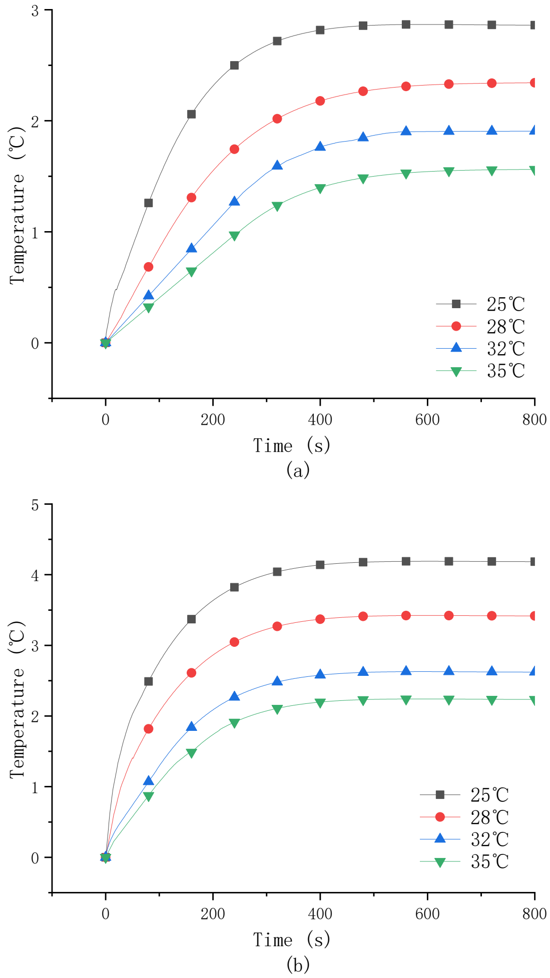


Fig. 3. ΔT of the battery pack in case 1 (a) traditional dry-cooling (b) with wet pad

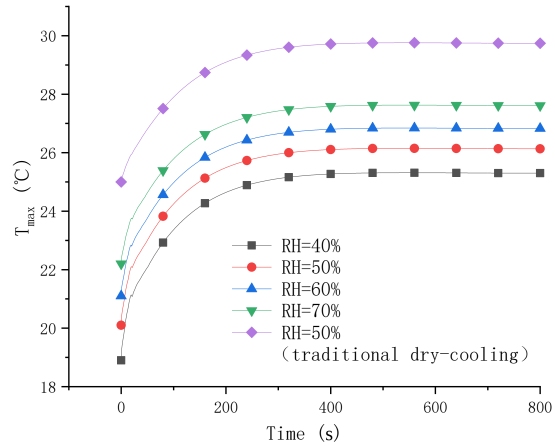


Fig. 4. T_{max} of the battery pack in case 2 (a) traditional dry-cooling (b) with wet pad

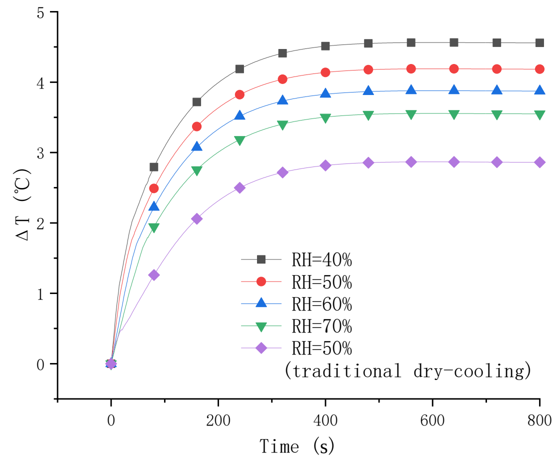


Fig. 5. ΔT of the battery pack in case 2 (a) traditional dry-cooling (b) with wet pad

2.4.2 Effect of ambient air RH

The influence of humidity on the heat dissipation of battery pack are not considered in this work. Therefore, the use of the wet pad exerts an impact on the thermal performance of the battery pack in the form of changing the inlet air temperature of battery pack. As shown in Table 3, at the same ambient dry bulb temperature of 25 °C, when ambient air RH increased from 40% to 70%, the inlet temperature of the battery drops by 6.1°C to 2.8 °C. Larger temperature drop and higher evaporative cooling efficiency, η, occurs at lower ambient air RH.

Table 3 performance of the wet pad at constant dry-bulb temperature of 25 °C and 3m/s air velocity

RH /%	inlet temperature of the battery / °C	ω kg/kg dry air	drop of temperature /°C	η/%
40	18.9	0.00786	6.1	70.50
50	20.1	0.00987	4.9	70.46
60	21.1	0.01188	3.9	70.43
70	22.2	0.01391	2.8	70.41

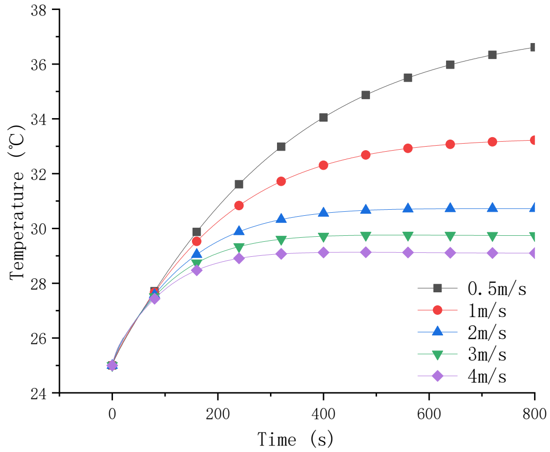
Similar trends of temperature gradient of the T_{max} can be observed at variable RH of ambient air with or without the wet pad, as displayed in Fig. 4. They are increased at the beginning of charging and stabled at around 400s. Under dry-cooling condition, the steady-state T_{max} is 29.8 °C, which is 2.2 °C to 4.5 °C higher as compared to that with the assistance of the wet pad.

As shown in Fig.4, the application of wet pad produces lower temperature of airflow and lower inlet temperature at the inlet of the battery pack brings larger temperature difference between the front row and back row of the battery pack.

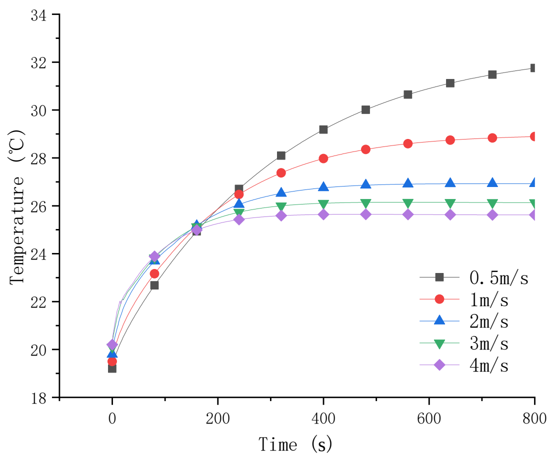
2.4.3 Effect of air velocity

Taking the case at 25 °C and 50% RH ambient air condition as example, the variations of maximum temperature and maximum temperature difference of batteries with ambient temperature at various air velocities are plotted in Fig. 6 and Fig. 7, respectively. As shown in Fig. 6(a), larger temperature increasing rate and higher T_{max} can be observed at lower air velocity. Under the dry-air cooling condition, T_{max} increases with time and stabilizes at 30.7 °C under 2 m/s air velocity.

Noticeably, it does not reach a steady state value at air velocity less than 1m/s, which may break-through the safety value of 40 °C if the charge is continued.



(a)



(b)

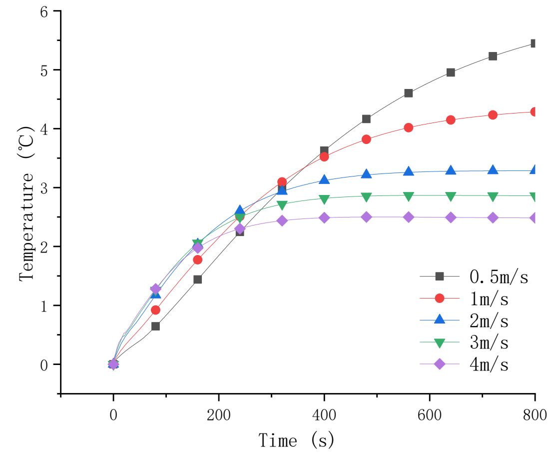
Fig. 6. T_{max} of the battery pack in case 3 (a) traditional dry-cooling (b) with wet pad

Better temperature uniformity can be observed at higher air velocity, as shown in Fig. 6(a). Maximum ΔT of 3.2°C and 2.4°C are obtained when the air velocity increased from 2m/s to 4m/s. It can be concluded that higher air velocity can bring lower surface temperature and more uniform temperature distribution of the battery pack.

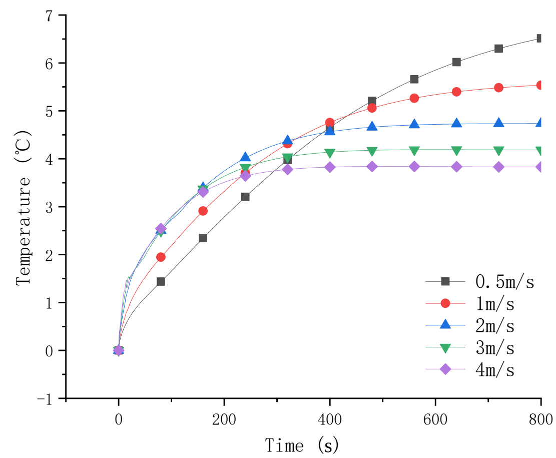
The use of wet pad as a heat transfer medium offers huge advantages in thermal management owing to its superior thermal properties compared to air. As shown in Table 4, the 25 °C ambient is pre-cooled to 19.2 °C to 20.2°C when air velocity increased from 0.5m/s to 4m/s.

Table 4 performance of wet pad at different air velocity

Air velocity m/s	Ambient air temperature /°C	ω g/kg dry air	Drop of temperature/°C	η /%
0.5	19.2	9.869	5.8	82.53
1	19.5	9.871	5.5	78.10
2	19.8	9.873	5.2	73.35
3	20.1	9.874	4.9	70.46
4	20.2	9.875	4.8	68.37



(a)



(b)

Fig. 7. *ΔT* of the battery pack in case 3 (a) traditional dry-cooling (b) with wet pad

The maximum surface temperature of the battery pack is observed ranging from 31.7 °C to 25.6°C when air velocity increased from 0.5 m/s to 4.0 m/s. The use of wet pad brings lower maximum surface temperature, but it plays an adverse role in the temperature uniformity of the battery pack, as it displayed in Fig. 6(b). At smaller air velocity equals and less than 1m/s, although the maximum surface temperature of the battery pack is reduced via the application of the wet pad, the temperature uniformity gets worse. Therefore, air velocity less than 1m/s is inappropriate for heat dissipation of batteries.

2.5 Conclusions

In this study, an air-cooling battery thermal management system assisted by a wet pad is simulated for a Li-ion battery pack to efficiently dissipate heat under various ambient conditions. Air can be pre-cooled when it passing through the wet pad due to the water evaporation. Higher evaporative cooling efficiency and cooler inlet air to the battery pack can be obtained at lower ambient air dry-bulb temperature, lower air RH as well as lower air velocity. Cooler inlet air to the battery pack results in reduced maximum surface temperature of the battery pack, but plays an adverse role in the maximum temperature difference. The wet pad is more capable to scorching weather compared to the traditional dry cooling system. Larger air velocity can enhance the heat transfer between air and the battery pack, suppressing the maximum temperature of the battery pack. Air velocity less than 1m/s is inappropriate for heat dissipation of batteries.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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