STUDENT RESEARCH PROJECT GRANT 2023-2024

Battery Thermal Management via Evaporative Cooling

Report by:

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ABSTRACT

Thermal management is critical to safety, stability, and durability of battery energy storage systems. Existing passive and active air cooling are not competent when the cooling performance, energy efficiency and cost of the thermal management system are drawing concurrent concerns. Here we propose dew-point evaporative cooling as a novel active air-cooling approach for large battery systems. Its capability of cooling the air towards its dew- point temperature with simple working principle and great electrical efficiency offers an ideal solution. Therefore, a scalable dew-point evaporative cooling technology was developed, and a large-scale cooler was constructed which could deliver 8.9-10 coefficient of performance (COP). The potential of dew- point evaporative cooling for battery cooling was explored via the multiphysics coupling of battery and cooler models. This study elucidates that dew-point evaporative cooling can efficiently cool a battery by 3.0–13.6 C lower than the cases with only forced convection, and control the battery operating temperature within an ideal operating range of 20–40 ◦C.

Contents

1. Introduction

The rapid advancement in lithium-ion battery technology, essential for energy storage in electric vehicles and grid systems, comes with challenges in managing heat generated during charging and discharging. As batteries operate at temper- atures exceeding the optimal 20–40°C range, excessive heat can lead to battery degradation, reduced efficiency, or even thermal runaway. Conventional air and liquid cooling systems are commonly used but may not be sufficiently effective, particularly in large-scale systems. The proposed alternative is dew-point evapo- rative cooling (DPEC), which promises to improve energy efficiency and cooling capacity.

2. Dew-Point Evaporative Cooling Concept

The DPEC system operates by cooling the supply air towards its dew point temperature using water evaporation, achieving high cooling efficiency. This method can efficiently dissipate battery-generated heat, potentially lowering the battery temperature by 3.0–13.6°C compared to traditional air-cooling techniques.

3. Physics of Dew-point Evaporative Cooling

The dew-point evaporative cooler operates based on heat and mass transfer principles, utilizing latent heat from water evaporation to cool supply air towards its dew-point temperature. This section will explore the governing equations in- volved in the process.

3.1. Heat Transfer in Dew-point Evaporative Cooling

The heat transfer in the cooler is primarily driven by the evaporation of water in the wet channels, which absorbs sensible heat from the supply air. The cooling capacity of the cooler is calculated by the change in enthalpy of the product air before and after the cooler. The relationship is given by:

$$Q = \rho V_p(h_{su} - h_p) = \rho a V_p C_p(T_{su} - T_p) \tag{1}$$

This equation represents the energy removed from the air as it passes through the cooler.

3.2. Efficiency of the Cooler (Coefficient of Performance - COP)

The efficiency of the evaporative cooler, or the Coefficient of Performance (COP), is defined as the ratio of cooling capacity Q to the electrical power con- sumption W:

$$COP = \frac{Q}{W} \tag{2}$$

Where W is the power consumed by the cooler's air blowers, which maintain airflow through the cooler. The COP values achieved in the experiments ranged from 8.9 to 10, indicating very high energy efficiency compared to conventional air-conditioning systems.

3.3. Momentum, Energy, and Mass Balances

The air flows through the dry and wet channels in the cooler. In both the supply air and working air regions, momentum, and energy balances govern the process.

For the momentum balance in the supply air and working air:

$$\rho_a(u.\nabla)u = -\nabla P + \mu\nabla^2 u$$

(3) The energy balance in the air stream:

$$\rho_a C_p(u.T) = k\nabla^2 T \tag{4}$$

Where k is the thermal conductivity of air. In the wet channels, the mass balance for the water vapor concentration $\rho_v.u.\nabla\rho_v = D_{va}\nabla^2\rho_v$(5) Where D_{va} is the diffu- sion coefficient of water vapor in the air.

These equations describe the fluid flow and heat transfer mechanisms in the cooler, demonstrating how latent heat transfer (from water evaporation) cools the supply air.

3.4. Channel Plate and Water Film

The channel plate, which separates the wet and dry air channels, facilitates heat and mass transfer. The energy balance in the channel plate is described as:

$$k\nabla^2 T = 0 \tag{6}$$

4. Battery Kinetics and Thermal Management

The mathematical modeling of battery kinetics integrates electrochemical and thermal effects. The large-format 20 Ah lithium iron phosphate (LFP) pouch cells generate heat due to electrochemical reactions, Joule heating, and entropic changes. This section describes the battery kinematics through the use of pseudo- 4D (P4D) electrochemical-thermal models.

4.1. Electrochemical Model

Lithium-ion intercalation into solid particles within the battery occurs during charging and discharging. The charge and mass balances in the solid and liquid phases of the battery are key to understanding these processes. For the solid phase, the charge balance is:

$$\nabla i_s = -ai \tag{7}$$

For the liquid phase, the charge balance is:

$$\nabla i = ai \tag{8}$$

In the solid particles, lithium diffusion follows Fick's law:

$$\frac{\partial c_s}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(D_s r^2 \frac{\partial c_s}{\partial r}\right) \tag{9}$$

The Butler-Volmer equation describes the kinetics of the electrochemical reactions occurring on the electrode surfaces:

$$i = i_0 \, c^{\alpha} \left(c_{s\,\max} - c_{s\,\mathrm{surf}}\right)^{\alpha} c^{1-\alpha} \left[\exp\left(\frac{\alpha F\eta}{RT}\right) - \exp\left(\frac{-(1-\alpha)F\eta}{RT}\right)\right] \tag{10}$$

4.2. Thermal Model

The battery generates heat due to Joule heating, reaction heat, and entropic heat. The total heat generation rate within the battery is given by:

$$q = \sigma_{\mathrm{eff}} \nabla \varphi_s \cdot \nabla \varphi_s + \kappa_{\mathrm{eff}} \nabla \varphi_l \cdot \nabla \varphi_l + ai\,(\eta + T\Delta S)$$

(11) The energy balance equation for the battery thermal model is expressed as:

$$\rho C \frac{\partial T}{\partial t} = \nabla .(k \nabla T) + q \tag{12}$$

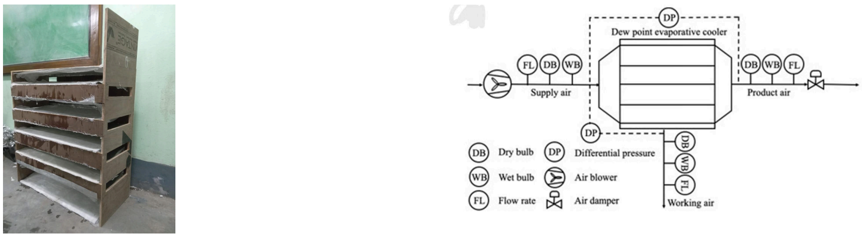
The convective boundary condition for heat transfer on the battery surface is given by:

$$n.(-k \nabla T) = h(T - T_{amb}) \tag{13}$$

These equations combine electrochemical and thermal processes, allowing us to model the battery's thermal behavior accurately.

5. Experimental Setup

Thermocouples were strategically installed at multiple points throughout the system to monitor and record the temperatures of various air streams. These ther- mocouples measured the temperature of the inlet air as it entered the system, en- suring precise data on the initial conditions. Additionally, they captured the tem- perature of the product air, which is the air that has interacted with the system's processes and is crucial for evaluating performance and efficiency. Finally, the thermocouples recorded the temperature of the outgoing working air, providing insights into how effectively the system is expelling air after processing. By cap- turing these temperature readings, we can gain a comprehensive understanding of the thermal dynamics within the system, which is essential for optimizing performance and ensuring that the system operates within its designed parameters.



(a) Model

(b) Layout

Figure 1: Model and Setup

6. Results

The experiments showed that DPEC could effectively reduce the battery op- erating temperature, ensuring it remained within the optimal range even during high-rate (4C) discharging.

Table 1: Calculated values for theoretical validation

$T_{supply}(C)$	$T_{workingout}$ (C)	δT (C)
33.7	30.5	3.2

Figure 2 Air temperature at exit

Figure 3 Air temperature at entry

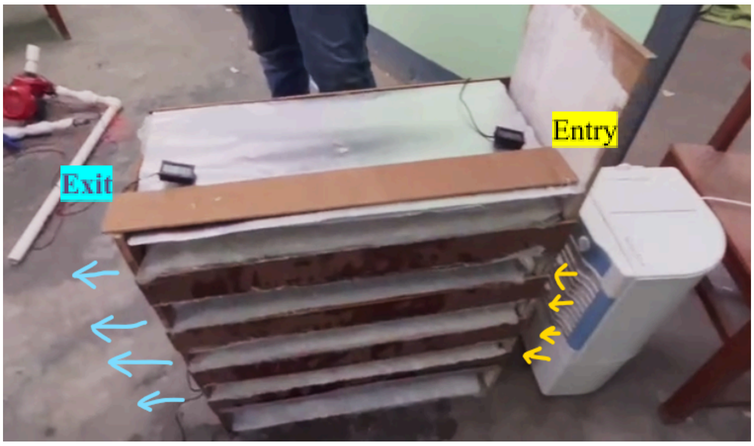


Figure 5 Working setup

7. Discussion

The thermodynamic process experienced by the air within the dry channel is illustrated in the diagram below. This process involves a series of changes in the air’s heat, pressure, and volume as it moves through the system. The depiction be- low offers a detailed representation of how the air undergoes these thermodynamic transformations while traversing the dry channel. By examining the process, one can observe the specific behavior of the air, highlighting its thermodynamic evo- lution during this passage. The following illustration provides a visual breakdown of these changes and their impact on the air inside the dry channel.

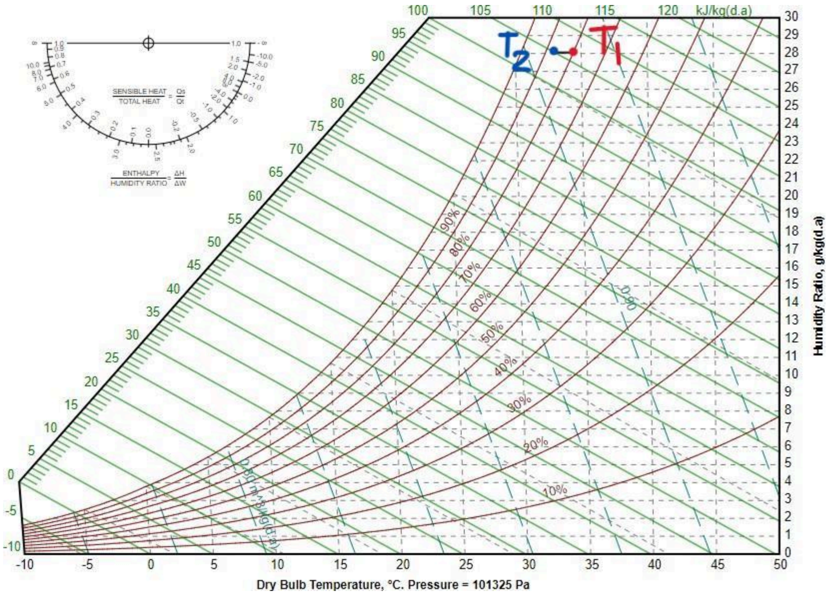


Figure 2: Psychometric Chart showing Evaporative Cooling

8. Costs

We had recently purchased several items needed to build our evaporative cooler unit, carefully selecting each component required for the assembly. To ensure transparency and keep track of our spending, we decided to organize all the ex- penses associated with these purchases. We compiled a detailed table to clearly show the costs of every item we bought, which provides a comprehensive break- down of the total expenditure. This table serves as an efficient way to document all the materials involved in the construction process, ensuring we stay within budget and have a clear overview of our financial outlay. By listing the costs, we can easily assess and manage the overall investment required for completing the evaporative cooler unit.

Table 2: Cost Table

ITEMS	NO	COST
TABLE FAN	1	1500
CPU FAN	5	1200
GAUGE	20	800
WOOD STAPLER	1	1800
PLYWOOD	2	2200
PLY CUTTING	1	700
ALUMINIUM FOIL	20sq ft	2500
FEVICOL	5	500
PAINTS		500
CIRCUITS		900
DATA LOGGER	2	5000
TRAVEL COST		800
PIPES	10	1000
WATER TANK	1	1100
Glue Gun	1	100
TOTAL		**21500**

Table 3: Items to be bought

ITEMS	NO	COST
Dry and Wet bulb Thermometers	2	2000
Air-Velocity Transducer	1	5000
Power Meter	1	2000
Honeycomb		4000
Thermal Paste	20	6000
Others		2000
TOTAL		**21000**

Through the help of the allocated funds and limited equipment availability, we managed a recorded temperature difference of above 3 degrees. Costly acces- sories like thermal paste, dry and wet bulb thermometer, honeycomb wall, and air velocity transducer are extremely important for our current project and will im- prove performance by several grades. We are very much hopeful of producing a greater cooling effect with all the necessary types of equipment that are due for the experiment but can't be bought due to a shortage of funds. To be exact, we need around 20k for further work.

9. Conclusion

Dew-point evaporative cooling presents a highly efficient solution for ther- mal management in battery energy storage systems. By integrating DPEC, it is possible to maintain optimal battery temperatures, enhance safety, and extend battery longevity. Additionally, the scalability of this technology makes it suit- able for both small and large-scale battery systems. The study's findings support the broader adoption of DPEC in the growing field of energy storage solutions, particularly as demand for efficient cooling systems rises with advancements in renewable energy storage.

10. References

The following references were integral to our research and analysis. These sources provided the foundational knowledge and context necessary for our study. We extensively reviewed and utilized these references to ensure the accuracy and depth of our work. Each reference offered valuable insights, methodologies, or data that significantly contributed to our findings. By consulting these sources, we were able to support our conclusions and ensure that our research was both well-informed and credible.

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