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CFD Analysis of Non-Uniform Circumferential Fin Distribution for Enhanced Battery Thermal Management

Ali Alawi, Ahmed Saeed, Mohammad Al Janaideh, Mostafa H. Sharqawy*
School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, Canada
*melsharq@uoguelph.ca

Abstract**—**The reliance on Lithium-Ion Batteries (LIBs) as a primary energy source and storage system has grown significantly, particularly in the transportation sector, as a sustainable alternative to fossil fuels. However, the effective thermal management of LIBs remains a critical challenge, especially under different operational loads and varying environmental conditions. This study numerically investigates the thermal performance of an air-cooled battery thermal management system (BTMS) with circumferential fins applied to a single cylindrical LIB cell (LFP 32700). The study focuses on the impact of key parameters, including discharge rates (1C, 1.5C, and 2C), fin spacing (4–32 mm), and non-uniform distribution of fins on the surface of a battery cell using two distribution Cases. The Multi-Scale Multi-Domain (MSMD) and Equivalent Circuit Model (ECM) equations were employed to simulate battery operation loads using ANSYS-FLUENT software. The results demonstrate that an optimal spacing of 9–11 mm between the fins and an arrangement of 10 fins per battery height significantly enhances thermal performance by reducing temperature variations and improving heat transfer.

Keywords-component; Circumferential Fins, BTMS, CFD, LIB

I. Introduction

In recent years, global efforts to reduce greenhouse gases (GHG), particularly CO_2 emissions from fossil fuel-powered vehicles, have increased [1]. Therefore, electric vehicles (EVs) have emerged as a competitive alternative to internal combustion engine vehicles (ICEVs), offering the advantages of zero emissions and greater energy efficiency [2]. At the core of EVs lies the battery, which serves as the primary power source. Lithium-ion batteries (LIBs) have gained significant popularity among battery technologies due to their high capacity, efficiency, and extended driving range [3]. On the other hand, EVs continue to encounter challenges related to thermal performance, which directly impact their lifespan, efficiency, and overall battery performance [4]. The battery thermal management system (BTMS) plays a crucial role in ensuring the battery operates within the optimal temperature range of 20 to 40 ºC [5]. One promising approach to further improving BTMS performance is integrating circumferential fins, which increase the heat transfer surface area and enhance the thermal distribution of heat generated by LIBs.

II. Literature review

A. Padalkar et al. [6] have numerically and experimentally investigated the influence of the horizontal circumferential fins with forced Air-BTMS on the LIB's temperature, considering the variation of the discharge rate [0.5C, 1C, 1.5C, 2C, 2.5C, 3C]. The findings revealed that the use of circumferential fins decreased the maximum temperature of the cell and enhanced heat dissipation. P. Chandra et al. [7] enhanced the convective heat transfer of the air-BTMS by integrating the uniform and non-uniform distribution of interrupted fins for 12-cylinder LIB. Compared with the base design, the proposed design enhanced the temperature homogeneity by 9.29% and decreased the average temperature by 5.646 K. W. Li et al. [8] proposed and investigated numerically the integration of air-BTMS with herringbone fins on the thermal performance of 12 cylindrical LIBs. The cells have been arranged in staggered and inline arrangements considering transverse pitch, longitudinal pitch, fin height, and fin number. The results revealed that the proposed design has significantly enhanced the uniformity of the temperature. Moreover, the average temperature decreased by 3.687 K in inline configurations and 4.15 K in staggered configurations. Similarly, A. Alzwayi et al. [9] studied the effect of using air-BTMS with vertical and spiral cooling fins on the thermal performance of a single cylindrical lithium-ion battery cell, considering the fins' length, thickness, position, number, and rotation. The result demonstrated that at a low Reynold's number, the vertical fins reduced the maximum cell temperature by up to 35%. On the other hand, spiral fins decreased the cell temperature by 3.2% with 65.6% less material usage compared to vertical fins. M. Öztop et al. [10] Enhanced the air-BTMS of the cylindrical Li-ion batteries by using longitudinal fins. The findings revealed that the proposed design could reduce the battery cell's maximum temperature to within the optimal range of 15–35°C.

III. PROBLEM STATEMENT

The thermal sensitivity of LIBs generates substantial obstructions to their performance, safety, and operating life. The non-homogenous distribution of temperatures inside battery packs not only leads to thermal hotspots but also less efficiency, shorter life cycles, and significant safety risks. An optimized BTMS is required to overcome these challenges. While air-BTMS are low-cost, non-complex, and easy to maintain, they commonly operate ineffectively due to insufficient heat capacity and inconsistent airflow distribution. Using circumferential fins in BTMS design enhances thermal behavior by ensuring uniform temperature distribution and reducing thermal hotspots. However, optimizing fin structures, such as fin number and distribution, is crucial for maintaining a balance between thermal performance and system weight. This study uses CFD modeling to study the effectiveness of air-BTMS with circumferential fins. The study intends to identify a suitable layout that provides excellent thermal performance and decreases system weight by adding circumferential fins, considering different fin spaces and numbers.

Since the temperature distribution along the battery cell is non-uniform, specifically, the lower part of the cell reveals slightly lower temperatures than the upper part. To address this non-uniformity, this study investigates the effect of varying the distribution of fins along the battery cell. Two different cases were considered for the fin distribution. In the first case, the upper part of the cell has (n+1) fins, while the lower part contains (n) fins, where (n) represents the number of fins. In the second case, the upper part has (2n) fins, and the lower part retains (n) fins.

A. Governing Equations

The governing equations that have been adopted for this study are as follows:

- Continuity equation:

The continuity equation represents the mass conservation principle, which states that the mass that enters the system must equal the mass that leaves the system plus the mass that accumulates in the system.

$$\frac{\partial \rho}{\partial t} + \nabla(\rho V) = 0 \qquad (1)$$

Where V is the velocity and ρ is the density of the working fluid.

In this study, the fluid is assumed to be incompressible (Ma<0.3), and the continuity equation changed to be:

$$\nabla(V) = 0 \qquad (2)$$

- The momentum equation:

The momentum equation of the fluid flow as follows:

$$\rho \frac{\partial V}{\partial t} = -\nabla \mathrm{P} + \mu \nabla^2 V \qquad (3)$$

Where the μ is the dynamic viscosity of the working fluid, and P is the static pressure.

The energy equation of the working fluid flow as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla\left(\rho C_p V T\right) = \nabla(\mathrm{k}\, \nabla \mathrm{T}) \qquad (4)$$

Where the T is the temperature of the fluid, ρ, k, and Cp represent the thermal conductivity of the working fluid. Moreover, V represents the velocity of the working fluid.

B. Geomtrey and Model

Due to its high energy density, long life cycle, and low self-discharge rate, the lithium-ion battery has been employed in this study [11]. The LFP 32700 has been used, and the specification of this type is represented in Table 1. Moreover, the properties of the LFP battery cell material for the active body and the Cathode/Anode are illustrated in Table 2.

Table 1: The specification of the LFP 32700 battery cell.

Battery model	Capacity (mAh)	Nominal voltage (V)	Minimum Voltage (V)	Maximum voltage (V)	Operating temperature (°C)
LFP 32,700	6000	3.2	2.5	4.2	Charge: 0 to 45 Discharge: 20 to 60

Table 2: The properties of the battery cell material.

Materials	Density (kg/ m^3)	Specific heat (J/kg K)	Thermal Conductivity (W/m K)
Active body material	2092	678	18.2
Cathode and Anode materials	8970	381	18.2

In this study, one LFP battery cell with a circumferential fin has been employed. Therefore, the battery model was built by ANSYS-FLUENT, as shown in Figure 1. Additionally, the flow domain was defined using the cylindrical battery with the following geometry: a diameter of 31 mm and a height of 68 mm for the active body zone of the battery, and for the cathode and anode tabs, the height is 2 mm with a diameter 31mm and 18mm, respectively. This battery has been placed inside a box with a height of 75 mm, a width of 50 mm, and a length of 50 mm for the airflow domain. Moreover, the working fluid is air with constant thermophysical properties (i.e., does not vary with time and temperature variation), as shown in Table 4. In this investigation, the square copper fin (35mm × 35mm) with a thickness of 1 mm has been used due to its higher conductivity and effectiveness [6]. The thermophysical properties of the fin are represented in Table 3.

Table 3: Fin properties.

Material	Thermal conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)
Copper	401	8990	381

Table 4: Air properties.

Working Fluid	Density (kg/m^3)	Specific heat (J/kg K)	Viscosity ($N.s/m^2$)	Thermal Conductivity (W/m K)
Air	1.225	1006.43	1.7894×10^{-5}	0.0242

To ensure that the model results are accurate and highly precise with optimum simulation time, the computational domain was discretized with a structured mesh, employing small elements near the battery surface and fins to capture detailed heat transfer phenomena. This resulted in a total of (546013 - 567093) elements with a mesh size of 0.9 mm. The quadrilateral mesh type has been used for this study due to the mesh's higher accuracy and uniform distribution for the selected geometry, as shown in Figure 2.

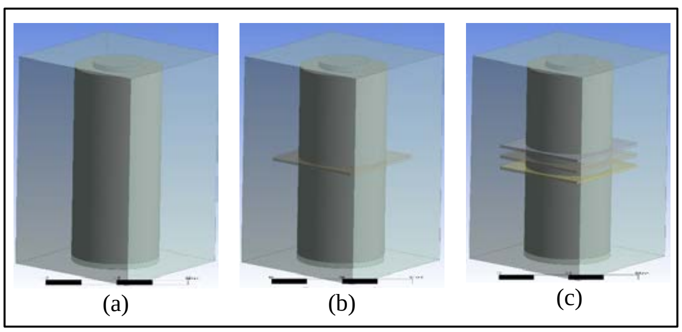


Figure 1: Model geometry a) cylinder without fins, b) cell with one fin in the middle, and c) cell with multi fins.

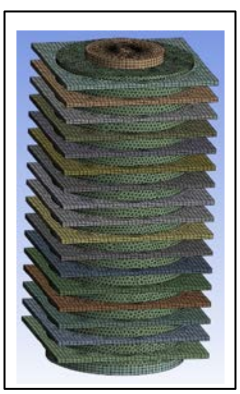


Figure 2: The mesh distribution of the battery cell with the maximum number of fins.

IV. CFD Setup

The transient CFD simulation for this study was carried out using 3D ANSYS Fluent with the buildup model for batteries [12]. In this model, the nominal, minimum voltage and capacity of the battery selected were defined, as shown in Table 1.

This study's key operating parameters include fin spacings ranging from 4 mm to 32 mm, the number of fins in upward and downward directions from the middle, and the discharge rates of 1C, 1.5C, and 2C.

The system's boundary conditions were selected to ensure that the model replicates real-world cases for heat and flow simulations. The boundary conditions for the battery, fins, passive zone, and active zone were selected to be at convection mode with heat transfer coefficient (10 $W/m^2.K$) and initial surface temperature of 293 K. At the inlet of the system, forced convection was selected with airflow at 1 m/s and an inlet temperature of 293 K. No-slip condition was taken to be the boundary condition of the side walls of the airflow channel. Additionally, the outlet of the airflow channel had a boundary condition of 0 Pa at gauge pressure.

Before starting the investigation, it was essential to establish a baseline and validate the computational model to ensure its accuracy and reliability. A preliminary simulation of the battery system was conducted under conditions of a 1C discharge rate and zero airflow, as shown in Fig . This simulation facilitated the analysis of temperature and voltage gradients across the battery, with the results subsequently compared against empirical data from prior experimental studies [6]. Additionally, this initial simulation played a critical role in identifying localized thermal hotspots and representing the temperature distribution across the battery surface. These results will play a critical role in the placement of fins to mitigate non-uniform temperature distribution and optimize heat transfer rate. Consequently, this setup established a robust framework for systematically evaluating the thermal performance of various fin configurations under different operational conditions.

V. Results & Discussions

This study examines the thermal performance of circumferential fins applied to a single cylindrical LIB (LFP 32700) battery, focusing on three critical parameters: fin spacing, discharge rate, and the number of fins. The investigation was conducted under forced air cooling conditions, with an airflow velocity of 1 m/s and an ambient temperature of 293 K. The study initialized with an analysis of fin spacing, utilizing a configuration comprising one fixed central fin and two additional fins positioned symmetrically upward and downward the central fin. The spacing between the fins was systematically varied from 4 mm to 32 mm in increments of 4 mm, while the battery was subjected to discharge rates of 1C, 1.5C, and 2C. Figures 3 and 4 illustrate temperature trends and thermal distribution patterns under the specified discharge rates and fin spacing configurations.

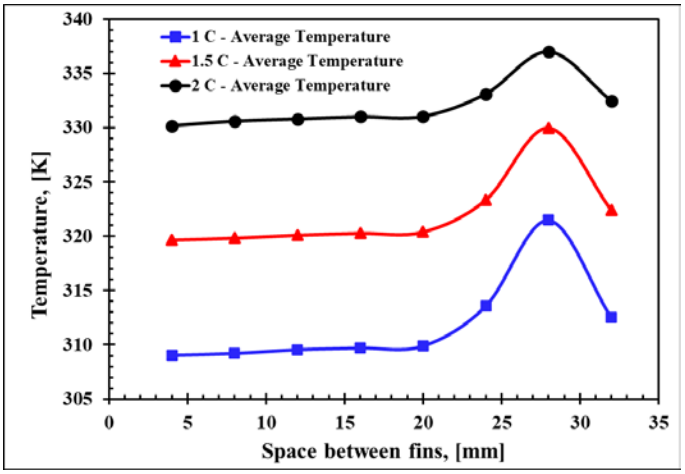


Figure 3: The effect of spacing between fins on the maximum and minimum temperatures of the battery cell under various discharge rates (1C, 1.5C, and 2C).

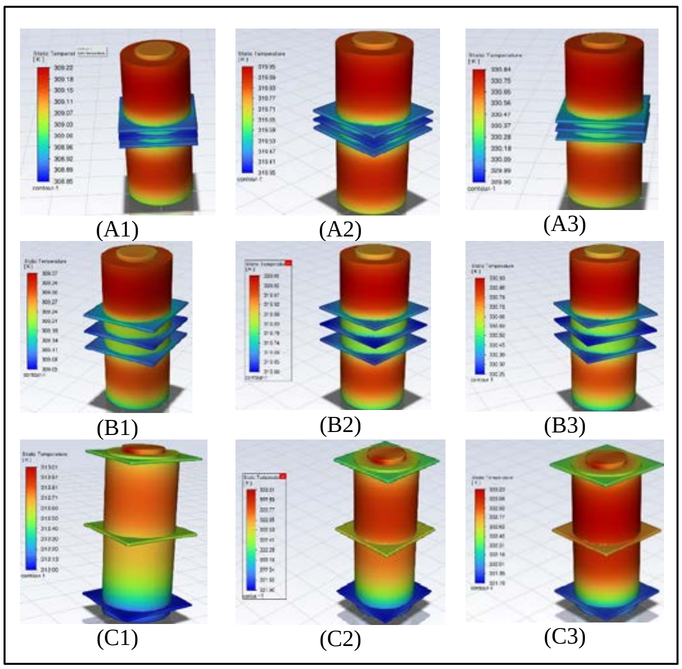


Figure 4: Temperature contours of the battery cell with fins at different spacing between the fins and difference discharge rates A1) 4 mm,1C A2) 4mm, 1.5C, A3) 4mm, 2C, B1) 8mm, 1C, B2) 8mm, 1.5C, B3) 8mm, 2C, C1) 32mm 1C, C2) 32mm,1.5C, C3) 32mm, 2C.

As shown in the Figures 3 and 4, the data reveals that the optimal average temperatures are achieved at a fin spacing of 4 mm. As the spacing between the fins increases, the temperature slightly increases, reaching its peak value at a spacing of 28 mm. This behavior can be attributed to the non-uniform temperature distribution across the battery surface, which arises from the heat generated during the discharge cycle. At this spacing point, thermal resistance formation impedes the heat dissipation rate, particularly in the upper region of the cell. Furthermore, the results indicate that temperature variability escalates with larger fin spacing, where the most favorable thermal performance is achieved within the range of 12 mm to 16 mm. Within this range, the average surface temperature is minimized, resulting in the most uniform temperature distribution along the battery.

Figures 5 and 6 illustrate the maximum and minimum temperature trends and temperature contours for Case 1, where the number of fins is (n+1) for the upper part and (n) for the lower part.

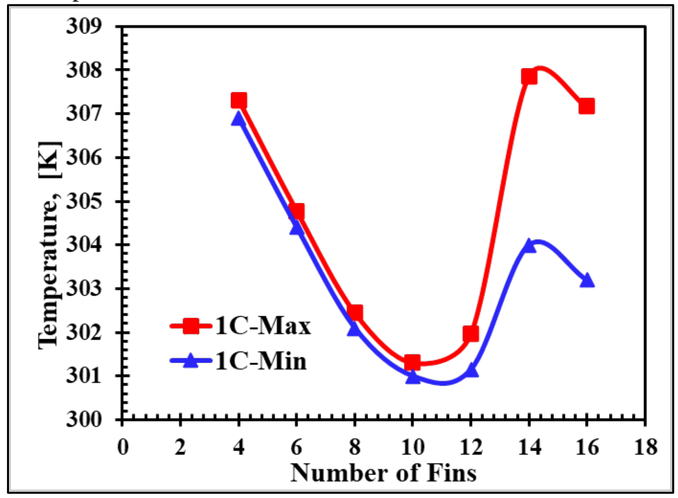


Figure 5: The effect of the number of fins for the first case on the maximum and minimum temperatures of the battery cell, considering the 1 C discharge rate.

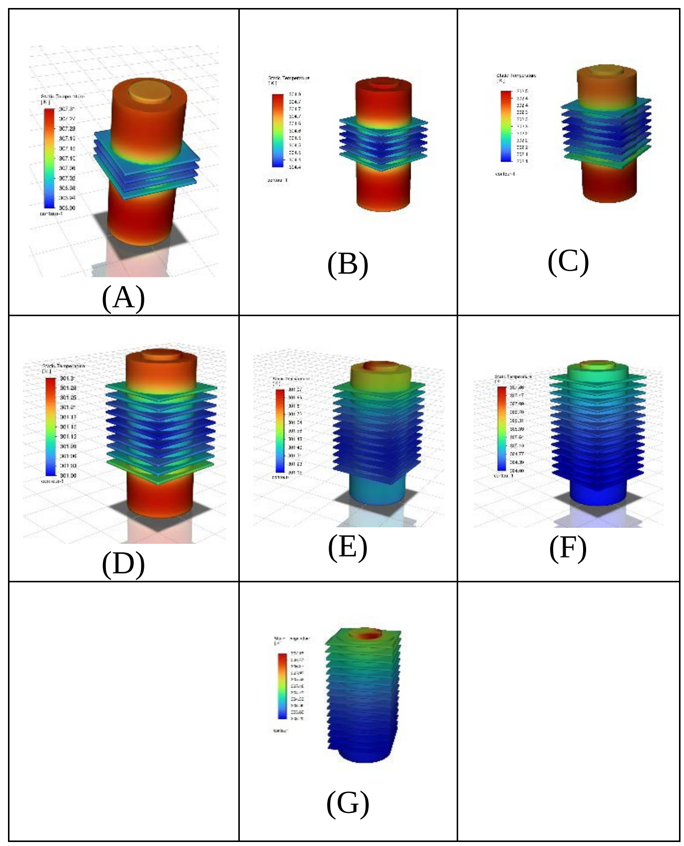
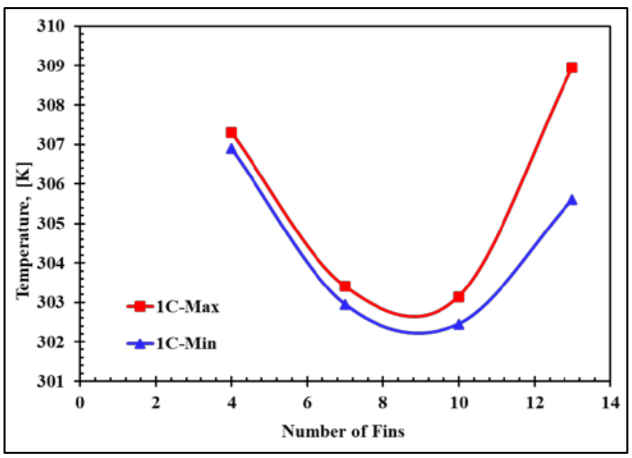


Figure 6: Temperature contours of the battery cell with fins at different spacing between the fins and difference discharge rates A1) 4 mm,1C

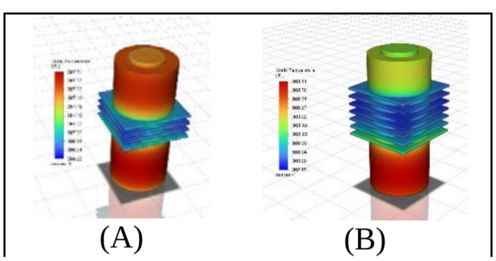
A2) 4mm, 1.5C, A3) 4mm, 2C, B1) 8mm, 1C, B2) 8mm, 1.5C, B3) 8mm, 2C, C1) 32mm 1C, C2) 32mm,1.5C, C3) 32mm, 2C.

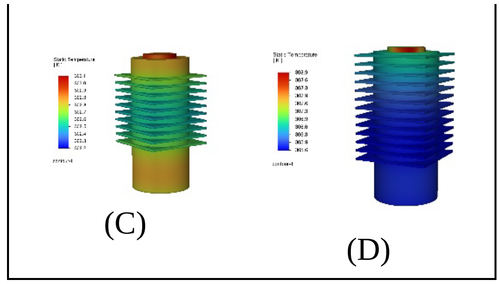
The spacing between the fins was maintained at a constant value of 4 mm across all configurations, and the simulations were conducted under a discharge rate of 1C and an airflow velocity of 1 m/s. As the number of fins increases up to 10, the temperature decreases dramatically, indicating that the additional fins enhance heat transfer rates and provide more uniform temperature distribution along the cell surface. However, beyond 10 fins, the temperature begins to rise drastically. This behavior can be explained when the number of fins increases, the space between them decreases, which can restrict airflow. Therefore, this restriction can lead to reduced convective heat transfer because the air can't flow freely to dissipate heat. Additionally, the non-uniform distribution of temperature along the battery surface causes some thermal resistance; hence, increasing the number of fins beyond the optimal number can impact the thermal performance of the system.

Figures 7 and 8 demonstrate the maximum and minimum temperature trends and temperature contours for Case 2, where the number of fins is (2n) for the upper part and (n) for the lower part. Like Case 1, increasing the number of fins reduces the temperature variations along the cell surface. Yet, this increase has an optimum number that shouldn't increase beyond, in which the temperature performance of the fins reduces and leads to insufficient heat removal from the cell.



[fig.7]





By comparing the results of the two cases, it is shown that Case 1 has a better uniform temperature distribution with an optimum number of fins equal to 10. With this fins' number, the temperature difference along the cell is about 0.3 degrees.

VI. Conclusion

This study investigated the thermal performance of a single cylindrical LIB (LFP 32700) with circumferential fins under forced air cooling and various discharge rates. The primary focus was on optimizing the BTMS by evaluating the effects of fin spacing, the number of fins, and the discharge rates on temperature distribution and heat dissipation. Using CFD modeling in ANSYS-FLUENT, the study demonstrated that circumferential fins significantly enhance thermal uniformity and reduce thermal hotspots.

The results revealed that fin spacing plays a critical role in thermal performance, with an optimal range of 9–11 mm providing the most uniform temperature distribution and minimal thermal resistance. Additionally, the study identified that increasing the number of fins improves heat removal up to a certain threshold. In both Cases, with (n+1) and (2n) fins in the upper part and (n) fins in the lower part, the best thermal performance is with an optimal fin of 10. Beyond this number, airflow restriction and increased thermal resistance led to reduced efficiency.

The study provides suggesting results to enhance the thermal performance of the battery system incorporated with fins. The future work aims to build a battery model with different numbers of cells, including additional parameters such as various flow rate velocities and fins geometries.

Acknowledgment

Put acknowledgments here (if applicable).

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