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Design and Optimization of Battery Thermal Management Systems in Electric Vehicles Using Advanced Simulation Techniques

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Abstract: Efficient thermal management is critical for ensuring the performance, safety, and longevity of batteries in electric vehicles (EVs). This study explores the design and optimization of battery thermal management systems using advanced simulation tools. Various fin configurations no fin, rectangular fins, elliptical fins, and irregular fins were designed using CATIA software, and their thermal and flow performance was analyzed through ANSYS and CFD simulations. The results demonstrate that while irregular fins exhibited the highest total heat flux (0.82196 W/m²), elliptical fins provided superior directional heat flux (0.095758 W/m²) and reduced eddy viscosity (7.185), leading to enhanced cooling efficiency and improved flow characteristics. These findings underline the significance of fin configuration in achieving optimal heat dissipation and efficient cooling for EV batteries. The elliptical fin design emerged as the most balanced and effective solution, making it a promising candidate for next-generation EV battery systems.

Keywords: Electric Vehicles (EVs), Battery Thermal Management, Fin Configurations, Heat Dissipation, Cooling Efficiency.

1. INTRODUCTION

The growing global focus on sustainable transportation has elevated electric vehicles (EVs) to the forefront of innovation, aiming to reduce greenhouse gas emissions and dependence on fossil fuels [1]. At the core of EV functionality lies the lithium-ion battery, which, while efficient, is highly susceptible to thermal challenges such as overheating, uneven temperature distribution, and potential thermal runaway [2]. These challenges necessitate robust thermal management systems (TMS) to ensure operational safety, enhance battery longevity, and maintain performance under varying conditions [3].

Battery thermal management systems (BTMS) employ a wide array of cooling and heating techniques, including liquid cooling, air cooling, phase change materials (PCMs), and heat dissipation fins. Among these, fin-based systems have proven to be a cost-effective and reliable solution due to their high thermal conductivity and adaptability to diverse battery configurations [4]. Recent advancements in elliptical fin designs, for instance, have demonstrated improved heat dissipation capabilities by optimizing surface area and enhancing airflow dynamics [5].

This study investigates the thermal performance of elliptical fin configurations for lithium-ion battery packs in EVs. Utilizing CATIA for fin design and ANSYS for thermal analysis, the research seeks to explore the effectiveness of these fins in maintaining optimal battery temperatures under various operating conditions. By advancing fin-based BTMS designs, this research aims to contribute significantly to the development of efficient and sustainable energy storage solutions for EVs [6].

2. METHODOLOGY

This research focuses on the development and optimization of a thermal management system for the battery in electric two-wheelers. The methodology is divided into several steps, including the design of the battery chamber, thermal analysis, and flow simulation using advanced simulation tools. The research follows a systematic approach to analyze and compare different fin configurations for efficient heat dissipation.

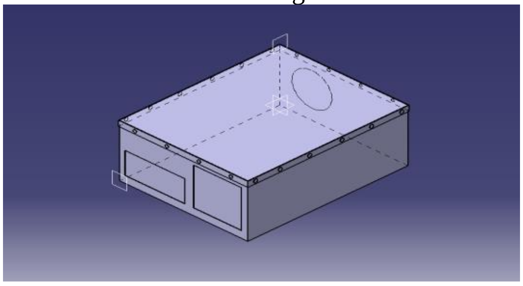
2.1 Design of Battery Chamber

The design of the battery chamber, which houses the battery pack and the cooling system, is a crucial aspect of thermal management. The design will be performed using CATIA software to create a 3D model of the battery chamber, considering:

- Geometrical Configurations: The chamber design will be optimized for airflow and heat dissipation. Various chamber designs with different internal configurations will be considered to improve thermal performance.
- Fin Configuration: Different fin types will be incorporated into the battery chamber to enhance heat dissipation. These will include rectangular, elliptical, and irregularly shaped fins, as well as a baseline design without fins.
- Material Selection: Appropriate materials will be selected for both the chamber and fins, ensuring high thermal conductivity and durability under varying environmental conditions.

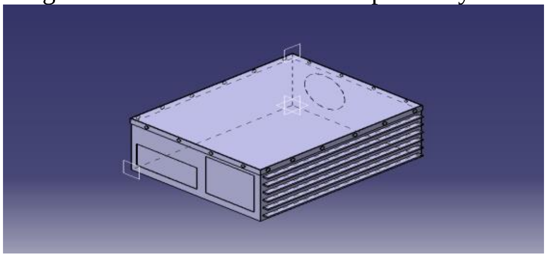
The CAD model of the battery chamber will serve as the foundation for subsequent thermal and flow simulations.
The following design variations will be analyzed:

- **No Fin Design**
  - A baseline model where no additional cooling fins are added.



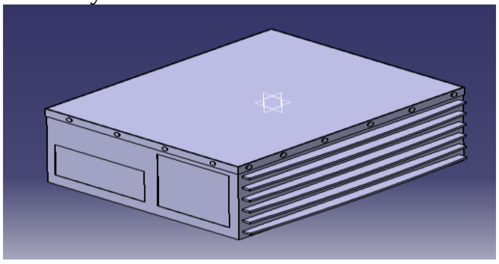
Fig(1) No Fin Design

- **Rectangular Fin Design**
  - Incorporating rectangular fins to enhance heat dissipation by increasing surface area.



Fig(2) Rectangular Fin Design

- Elliptical Fin Design
  - Using elliptical fins to study their effect on airflow and heat transfer efficiency.



Fig(3) Elliptical Fin Design

- **Irregular Fin Design**
  - Testing irregularly shaped fins to evaluate the effect of non-uniform shapes on cooling performance.

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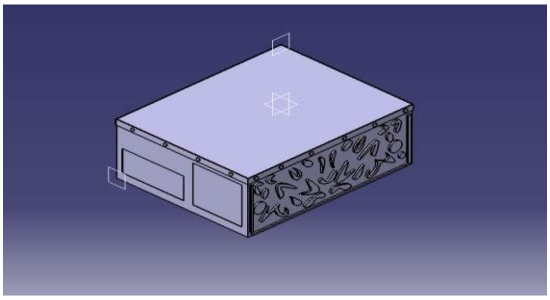


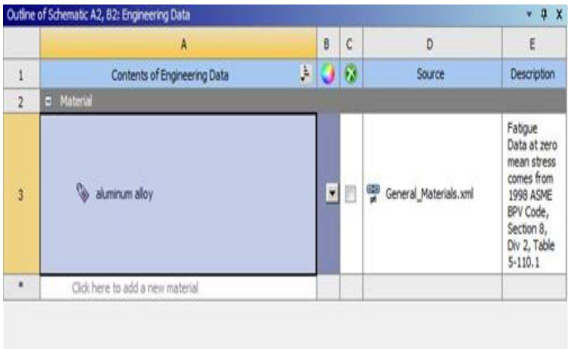
Fig(4) Elliptical Fin Design

2.2 Thermal Analysis

Thermal analysis was conducted using ANSYS software, with a focus on evaluating heat dissipation across the different fin configurations. The analysis considered the following parameters:

- Heat generation from the battery cells, simulated under typical operating conditions.
- Heat flux distribution across the fins and battery surface.
- Temperature distribution within the battery casing to assess thermal hotspots.

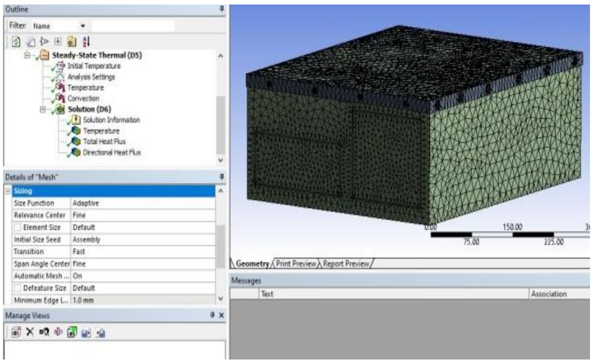
Boundary conditions such as ambient temperature, material properties, and heat generation rates were applied uniformly to each configuration to ensure consistency in the analysis.



Outline of Schematic A2, B2: Engineering Data

	A	B	C	D	E
1	Contents of Engineering Data			Source	Description
2	Material				
3	aluminum alloy		☐	General_Materials.xml	Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1
*	Click here to add a new material				

Fig(5) Material detail



Details of "Mesh"

Sizing	
Size Function	Adaptive
Relevance Center	Fine
☐ Element Size	Default
Initial Size Seed	Assembly
Transition	Fast
Span Angle Center	Fine
Automatic Mesh ...	On
☐ Defeature Size	Default
Minimum Edge L...	1.0 mm

Fig(6) Meshing View

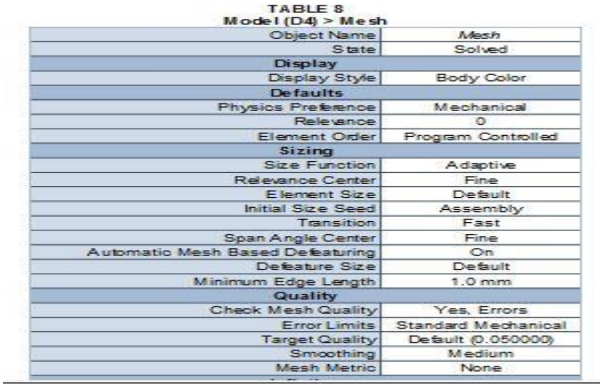
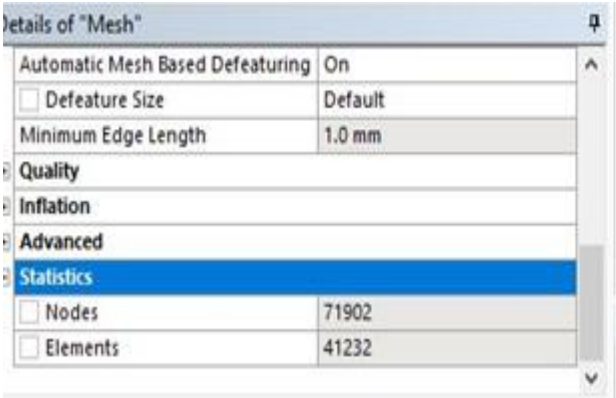


TABLE 8
Model (D4) > Mesh

Object Name	*Mesh*
State	Solved
Display	
Display Style	Body Color
Defaults	
Physics Preference	Mechanical
Relevance	0
Element Order	Program Controlled
Sizing	
Size Function	Adaptive
Relevance Center	Fine
Element Size	Default
Initial Size Seed	Assembly
Transition	Fast
Span Angle Center	Fine
Automatic Mesh Based Defeaturing	On
Defeature Size	Default
Minimum Edge Length	1.0 mm
Quality	
Check Mesh Quality	Yes, Errors
Error Limits	Standard Mechanical
Target Quality	Default (0.050000)
Smoothing	Medium
Mesh Metric	None

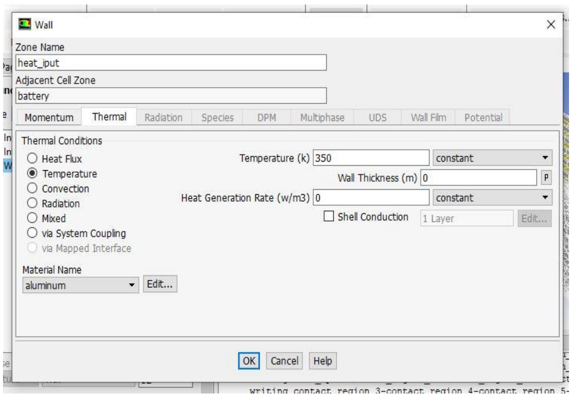
Fig(7) Meshing Details



Details of "Mesh"

Automatic Mesh Based Defeaturing	On
☐ Defeature Size	Default
Minimum Edge Length	1.0 mm
Quality	
Inflation	
Advanced	
Statistics	
☐ Nodes	71902
☐ Elements	41232

Fig(8) Elements counts



Wall

Zone Name: heat_iput

Adjacent Cell Zone: battery

Thermal Conditions
○ Heat Flux
● Temperature
○ Convection
○ Radiation
○ Mixed
○ via System Coupling
○ via Mapped Interface

Temperature (k): 350 constant

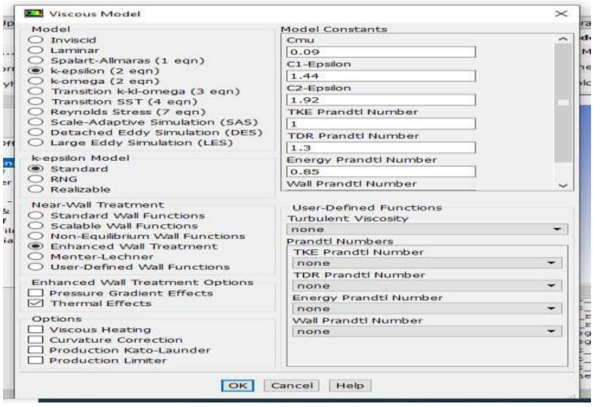
Wall Thickness (m): 0

Heat Generation Rate (w/m3): 0 constant

☐ Shell Conduction 1 Layer

Material Name: aluminum

Fig(9) Input Details



Viscous Model

Model
○ Inviscid
○ Laminar
○ Spalart-Allmaras (1 eqn)
● k-epsilon (2 eqn)
○ k-omega (2 eqn)
○ Transition k-kl-omega (3 eqn)
○ Transition SST (4 eqn)
○ Reynolds Stress (7 eqn)
○ Scale-Adaptive Simulation (SAS)
○ Detached Eddy Simulation (DES)
○ Large Eddy Simulation (LES)

k-epsilon Model
● Standard
○ RNG
○ Realizable

Near-Wall Treatment
○ Standard Wall Functions
○ Scalable Wall Functions
○ Non-Equilibrium Wall Functions
● Enhanced Wall Treatment
○ Menter-Lechner
○ User-Defined Wall Functions

Enhanced Wall Treatment Options
☐ Pressure Gradient Effects
☑ Thermal Effects

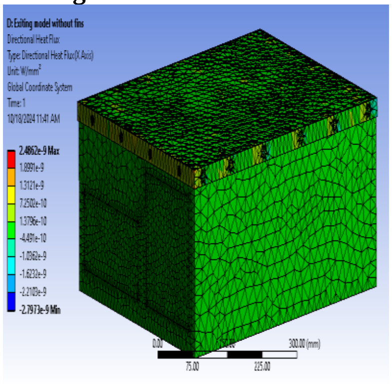
Options
☐ Viscous Heating
☐ Curvature Correction
☐ Production Kato-Launder
☐ Production Limiter

Model Constants
Cmu: 0.09
C1-Epsilon: 1.44
C2-Epsilon: 1.92
TKE Prandtl Number: 1
TDR Prandtl Number: 1.3
Energy Prandtl Number: 0.85
Wall Prandtl Number

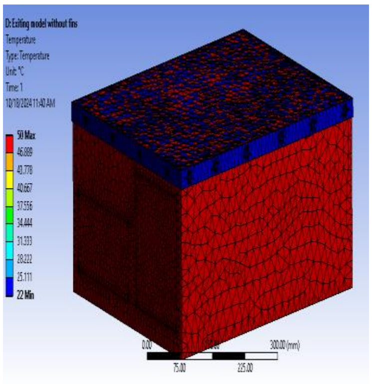
User-Defined Functions
Turbulent Viscosity: none
Prandtl Numbers
TKE Prandtl Number: none
TDR Prandtl Number: none
Energy Prandtl Number: none
Wall Prandtl Number: none

Fig(10) Results

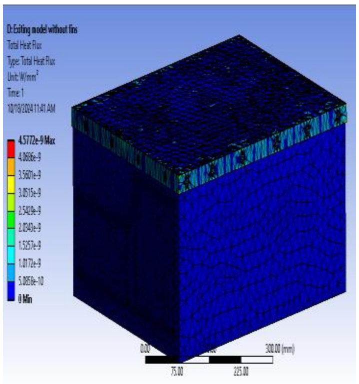
Exiting Without Fins



Fig(11) Directional Heat Flux

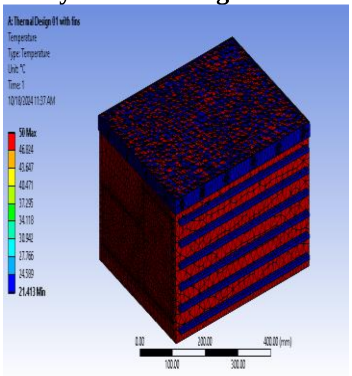


Fig(12) Temperature

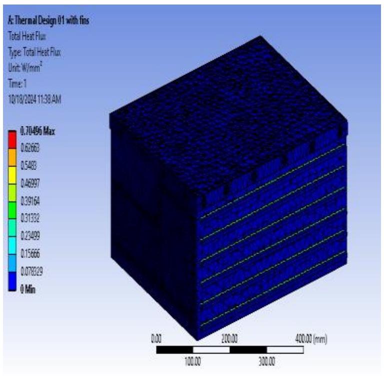


Fig(13) Total Heat Flux

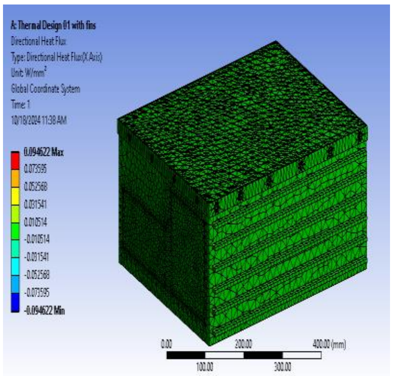
Battery with Rectangular Fins



Fig(14) Temperature

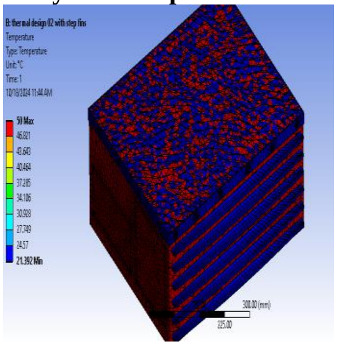


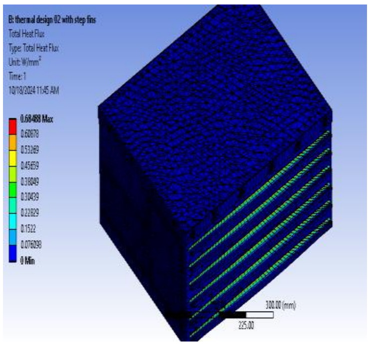
Fig(15) Total Heat Flux

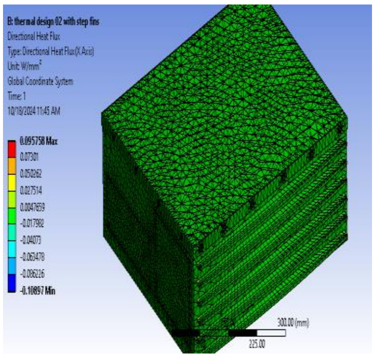


Fig(16)Directional Heat Flux

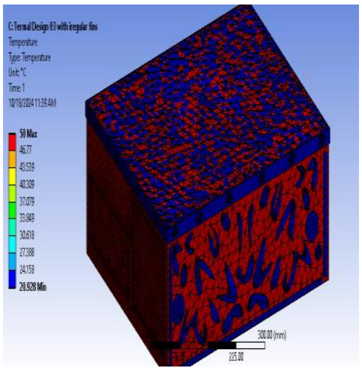
Battery with Elliptical fins

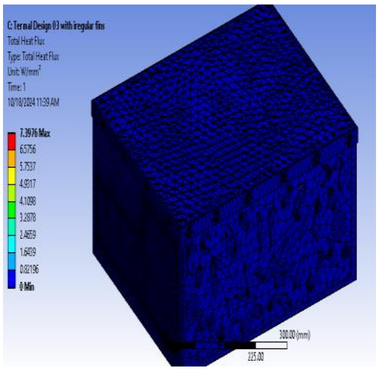

Fig(17) Temperature

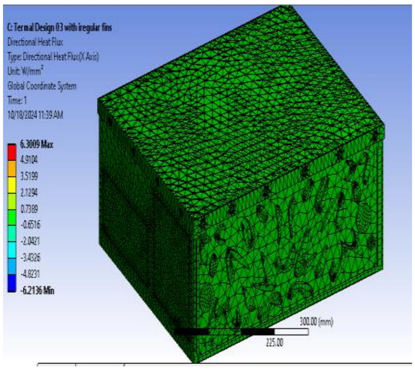

Fig(18) Total Heat Flux


Fig(19)Directional Heat Flux

Battery with Irregular shape fin


Fig(20) Temperature


Fig(21) Total Heat Flux


Fig(22)Directional Heat Flux

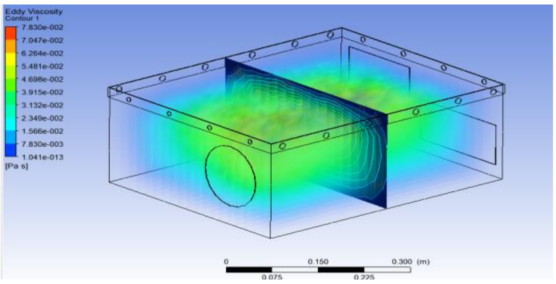
2.3 Flow Analysis

Computational Fluid Dynamics (CFD) analysis was performed to assess the cooling efficiency and flow characteristics of each fin configuration. The CFD simulations focused on:

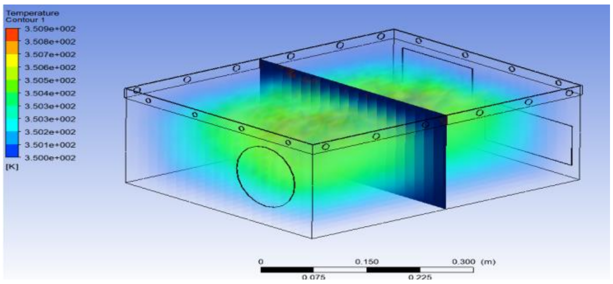
- Airflow dynamics: Studying the effect of different fin shapes on airflow around the battery casing.
- Turbulence and Eddy Viscosity: Measuring the levels of turbulence and eddy viscosity within the airflow, which impact cooling efficiency.
- Turbulence Kinetic Energy: Evaluating the energy associated with turbulent flow, contributing to the overall heat transfer effectiveness.

CFD simulations were set up with consistent inlet velocity and outlet pressure conditions to simulate typical cooling environments in electric vehicles.

Exiting Without Fins



Fig(23) Eddy Viscosity



Fig(24) Temperature

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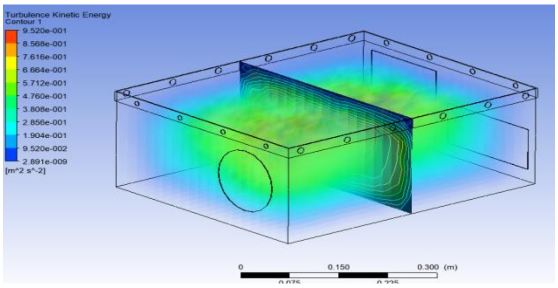
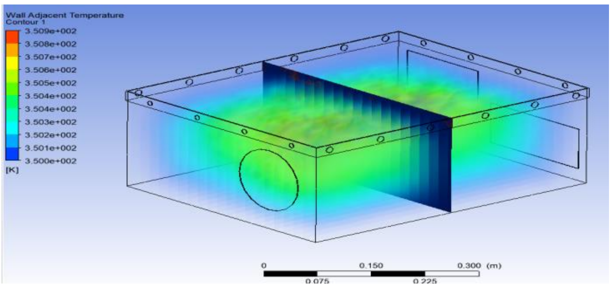
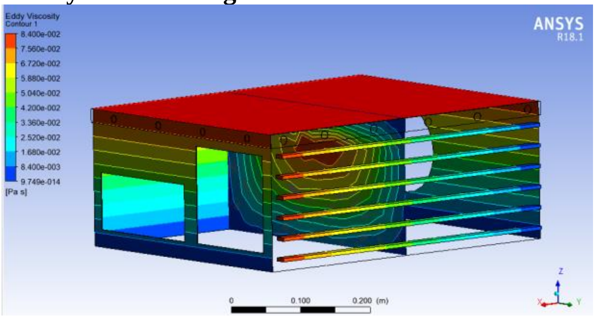


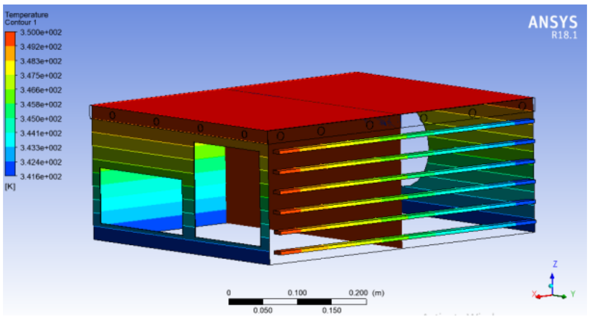
Fig(25) Turbulence Kinetic Energy



Fig(26) Wall Adjacent Temperature

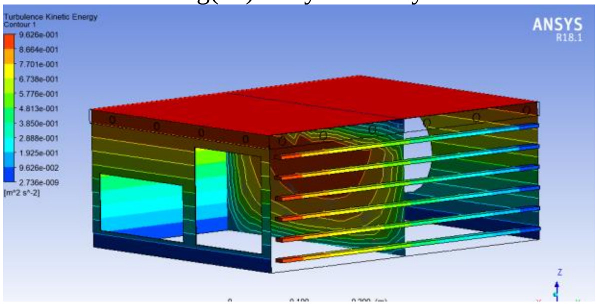
Battery with Rectangular Fins

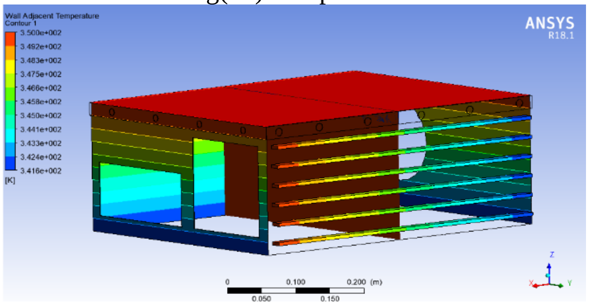




Fig(27) Eddy Viscosity

Fig(28) Temperature

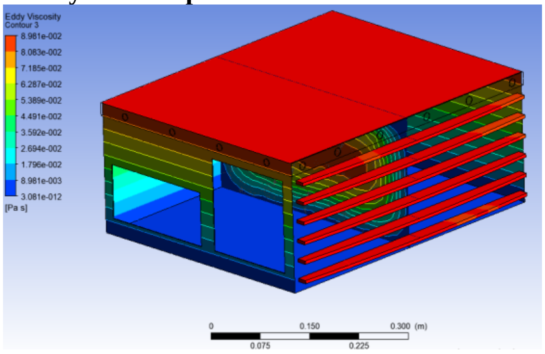


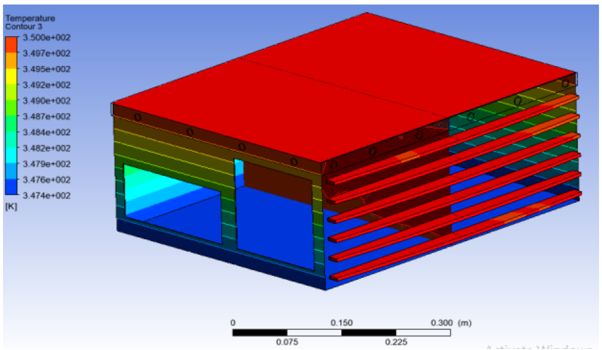


Fig(29) Turbulence Kinetic Energy

Fig(30) Wall Adjacent Temperature

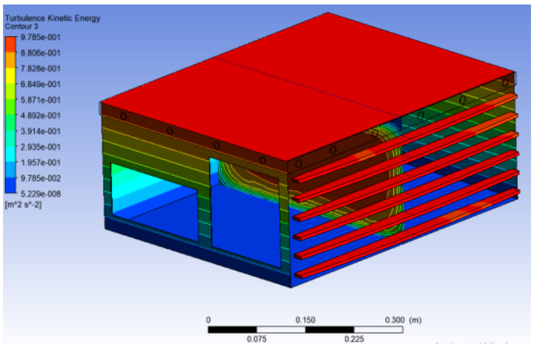
Battery with Elliptical fins



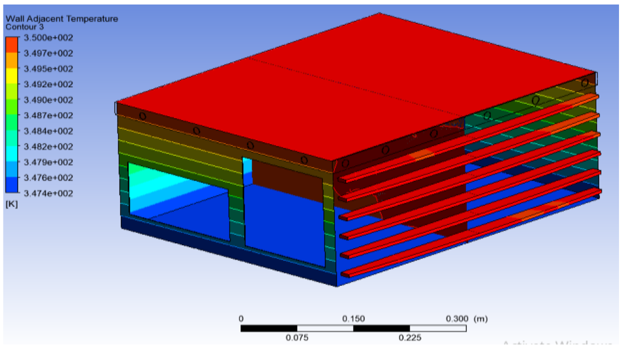


Fig(31) Eddy Viscosity

Fig(32) Temperature

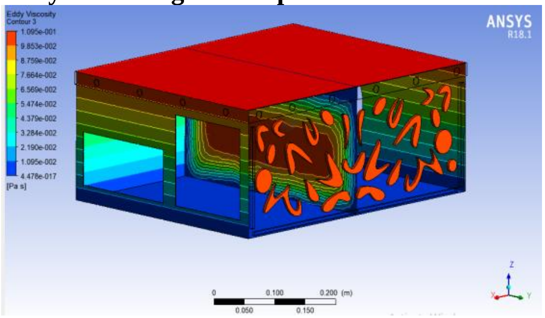


Fig(33) Turbulence Kinetic Energy

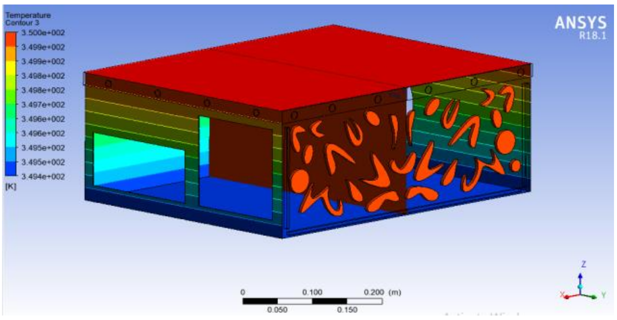


Fig(34) Wall Adjacent Temperature

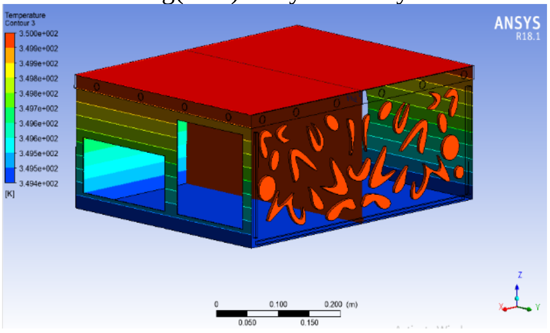
Battery with Irregular shape fin



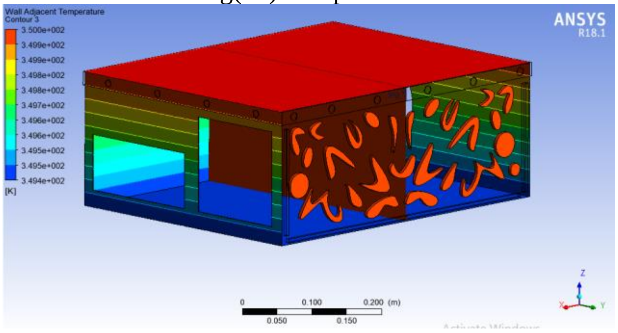
Fig(2.35) Eddy Viscosity



Fig(36) Temperature



Fig(37) Turbulence Kinetic Energy



Fig(38) Wall Adjacent Temperature

2.4 Performance Metrics and Comparative Analysis

The performance of different thermal management systems for electric vehicle batteries, featuring various fin configurations (without fins, rectangular fins, elliptical fins, and irregular fins), is evaluated using key metrics. These include battery temperature, crucial for ensuring efficiency and safety; total and directional heat flux, indicating heat dissipation effectiveness; eddy viscosity, which reflects fluid flow turbulence and enhances heat transfer; turbulence kinetic energy, which signifies the energy from turbulent flow promoting better heat transfer; and wall adjustment temperature, which ensures stable wall temperatures to prevent thermal hotspots. These metrics help identify the optimal thermal management solution for efficient battery performance.

3. RESULTS AND DISCUSSION

This section presents the results obtained from the thermal and flow analysis of the battery chamber with different fin configurations (without fins, rectangular fins, elliptical fins, and irregular fins) and discusses the implications of these results. The analysis was performed using Ansys and CFD Fluent software to evaluate the thermal performance, flow dynamics, and overall effectiveness of each design in managing the battery's temperature.

3.1 Thermal Results

The thermal results provide insights into how each fin design influences the temperature distribution within the battery chamber, the heat flux, and the thermal behavior of the system.

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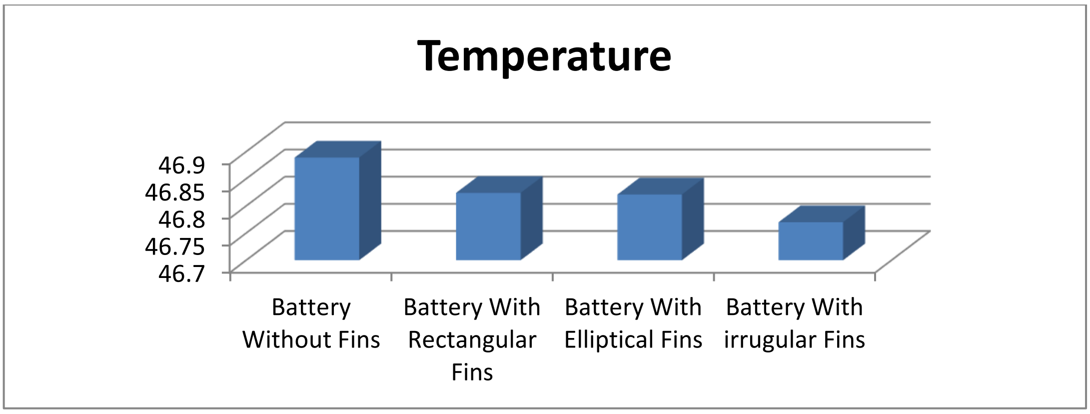
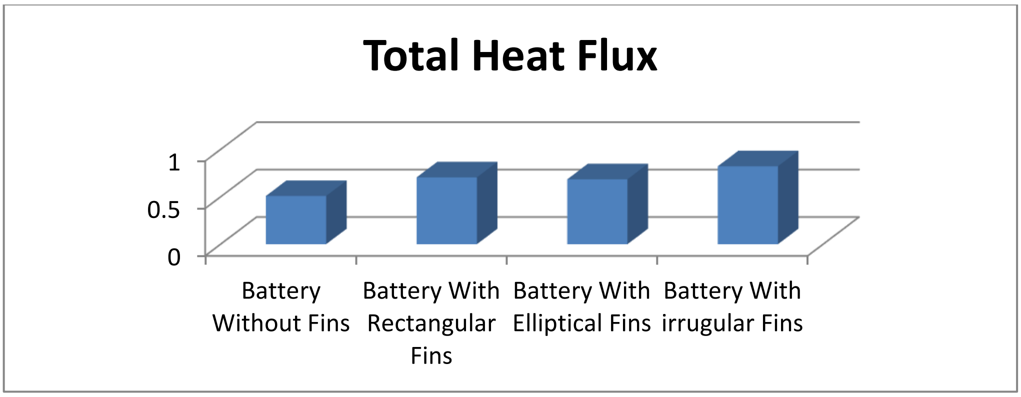
Table 1: Thermal Analysis Results for Different Fin Configurations

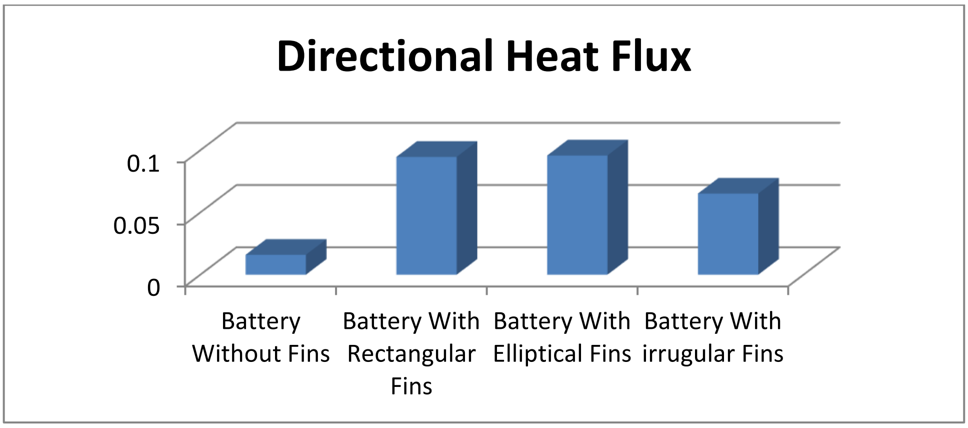
Configuration	Temperature (°C)	Total Heat Flux (W/m²)	Directional Heat Flux (W/m²)
No Fins	46.889	0.5086	0.01598
Rectangular Fins	46.824	0.70496	0.094622
Elliptical Fins	46.821	0.68488	0.095758
Irregular Fins	46.77	0.82196	0.06516



Fig(39) Temperature Distribution



Fig(40) Total Heat Flux



Fig(41) Directional Heat Flux

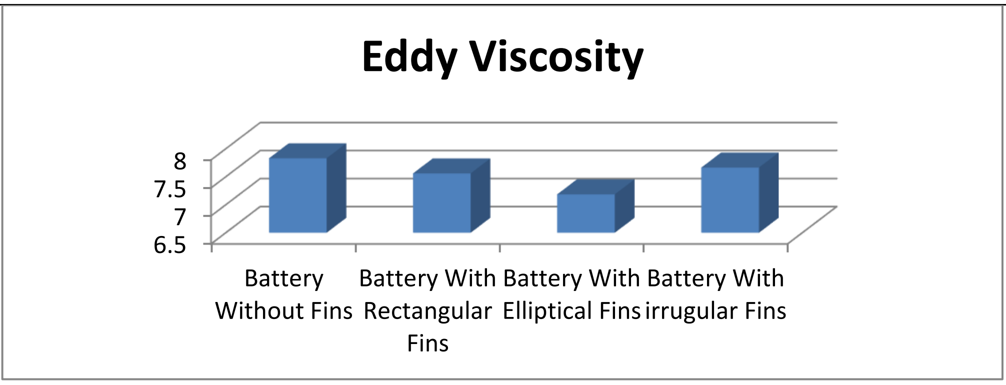
In terms of battery temperature, the irregular fin design performs best, maintaining the lowest temperature at 46.77°C, followed closely by rectangular and elliptical fins (46.824°C and 46.821°C, respectively). All fin configurations slightly reduce the temperature compared to the base case without fins (46.889°C), highlighting their role in temperature regulation. Regarding total heat flux, irregular fins again lead with the highest value of 0.82196 W/m², demonstrating superior heat dissipation, while rectangular and elliptical fins perform slightly better than the base case (0.70496 W/m² and 0.68488 W/m², respectively). For directional heat flux, elliptical fins are most effective (0.095758 W/m²), closely followed by rectangular fins (0.094622 W/m²), both outperforming irregular fins (0.06516 W/m²), which, while efficient in heat transfer, are less effective in directing heat away from the battery.

3.2 Flow Dynamics Results

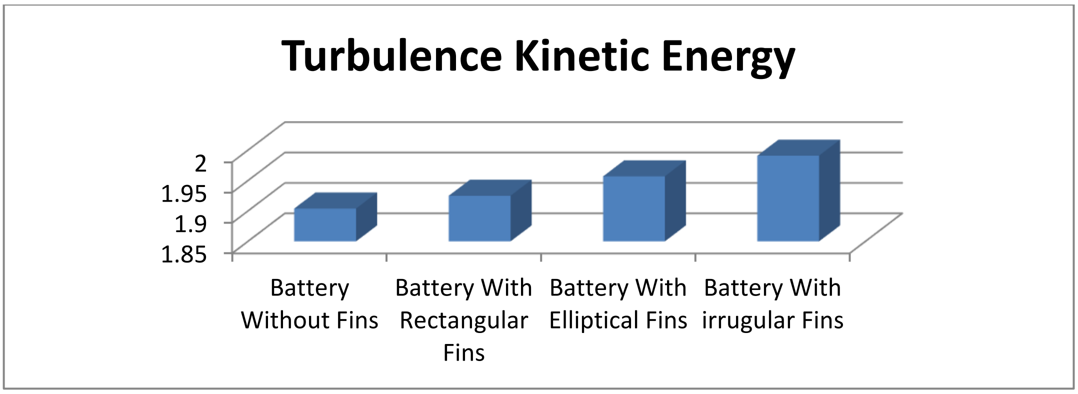
The flow dynamics results help in understanding the behavior of the airflow around the battery and its interaction with the fin configurations. The key parameters analyzed include eddy viscosity, turbulence kinetic energy, and wall adjustment temperature.

Table 2: Flow Analysis Results for Different Fin Configurations

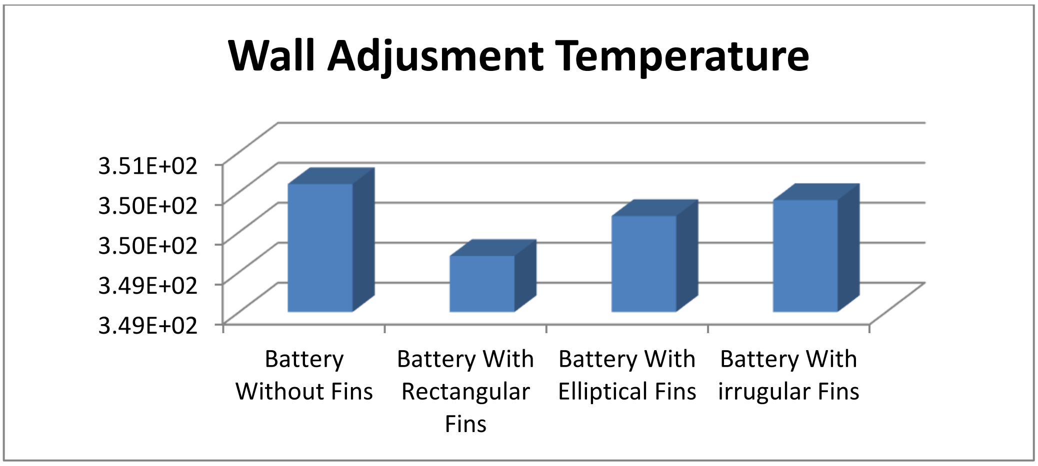
Configuration	Eddy Viscosity	Turbulence Kinetic Energy	Wall Adjustment Temperature
No Fins	7.83	1.904	350.2°C
Rectangular Fins	7.56	1.925	349.2°C
Elliptical Fins	7.185	1.957	349.7°C
Irregular Fins	7.664	1.991	349.9°C



Fig(41) Eddy Viscosity



Fig(42) Turbulence Kinetic Energy



Fig(43) Wall Adjustment Temperature

The comparative analysis reveals that the irregular fin design is the most effective for thermal management of electric vehicle batteries. It offers the lowest battery temperature, highest total heat flux, and improved turbulence kinetic energy, making it highly efficient at heat dissipation. However, it has a lower directional heat flux compared to elliptical and rectangular fins, which excel at directing heat away from the battery. The elliptical fins provide smoother airflow, with the lowest eddy viscosity (7.185 Pa.s), leading to more efficient heat dissipation. In contrast, the irregular fins, with higher eddy viscosity (7.664 Pa.s), create more turbulence, enhancing heat transfer despite potential inefficiencies in flow. Rectangular fins offer a balanced approach, with intermediate values for both eddy viscosity and turbulence kinetic energy. All designs maintain stable wall temperatures, ensuring long-term durability. In conclusion, the irregular fins are ideal for maximum heat dissipation, while elliptical fins are better suited for systems requiring a balance between heat dissipation and fluid flow efficiency.

4. CONCLUSION

The study aimed to investigate and compare the thermal management performance of various fin configurations without fins, rectangular fins, elliptical fins, and irregular fins for the battery chamber of an electric two-wheeler vehicle. The analysis was conducted using Ansys and CFD Fluent software to assess temperature distribution, heat flux, and flow dynamics under different design conditions.

From the results, it is clear that the inclusion of fins significantly improves the thermal management system of the battery chamber by reducing the battery temperature and enhancing heat dissipation. Among the different fin designs, the irregular fin configuration demonstrated the best overall performance. It resulted in the lowest battery temperature (46.77°C), the highest total heat flux (0.82196 W/m²), and the highest turbulence kinetic energy (1.991 k), making it the most effective in dissipating heat from the battery.

While the rectangular fins and elliptical fins also showed improvements in thermal performance compared to the baseline design (without fins), the irregular fins outperformed these configurations in terms of total heat flux and overall thermal efficiency. The elliptical fins, on the other hand, offered smoother flow dynamics, with the lowest eddy viscosity (7.185 Pa.s), which could be advantageous in certain designs where fluid flow stability is prioritized.

The results suggest that the irregular fin design is optimal for maximizing heat dissipation in an electric vehicle battery chamber, ensuring better battery performance and preventing thermal issues such as overheating. However, future work should focus on further refining the fin design to balance turbulence and heat dissipation more effectively, as well as experimental validation to confirm the simulation findings.

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