Thermal Flow Simulation and Cooling Design Optimization for a Formula SAE Electric Car Battery Pack

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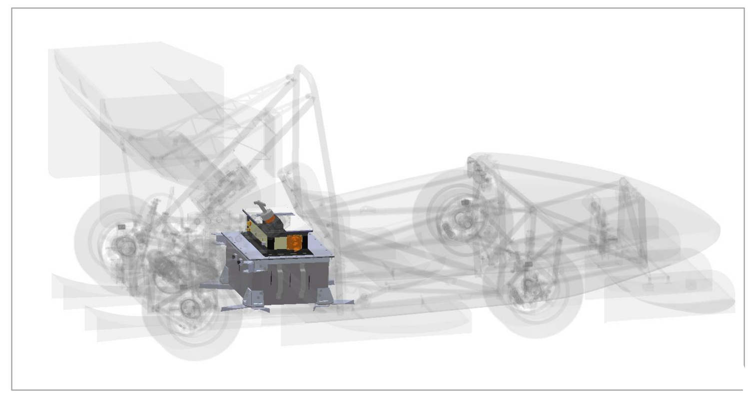
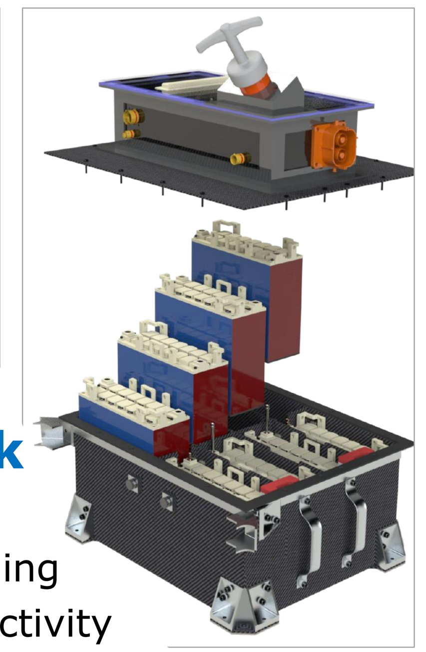
Electric Vehicle Battery: Li-ion

- The most popular but has a risk of thermal runaway by high temperature
- Performance is affected by temperature: optimal temperature between 15-35°C
- Battery pack thermal management → critical to safety & car performance





Formula SAE Electric Racing Car Battery Pack

- No active cooling system: Cooling by ambient air
- Battery pack is right behind the seat: Insufficient airflow for cooling
- Use carbon composite for cases: Significantly low thermal conductivity

So, how to improve the cooling efficiency of the battery pack for safety and performance?

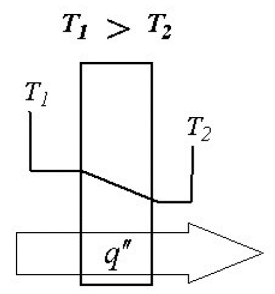
Heat Transfer Theory

Conduction

Energy is transported between parts of a continuum by the transfer of kinetic energy between particles or groups of particles at the atomic level.

$$q''_x = -k\frac{T_2 - T_1}{L}$$

q'' = heat flux
k = thermal conductivity
L = thickness
T_1, T_2 = surface temperature

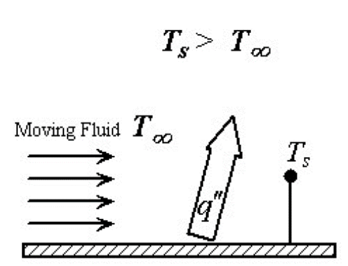


Convection

Energy transfer by fluid movement and molecular diffusion.

$$q = hA(T_W - T_\infty)$$

q = heat transfer rate
h = heat transfer coefficient
T_W = wall temperature
T_∞ = free stream fluid temperature

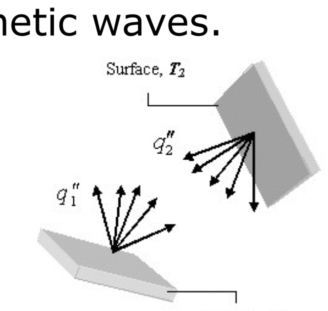


Radiation

Depends on the transfer of energy between surfaces by electromagnetic waves.

$$q = \sigma\varepsilon fA(T_1^4 - T_2^4)$$

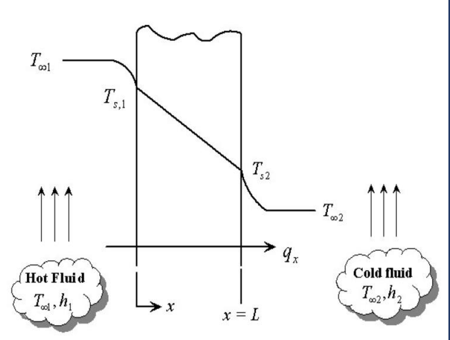
σ = Stefan-Boltzmann constant
ε = emissivity
f = geometrical factor
A = surface area



Series Circuit

The heat is first transferred from the hot fluid to the wall surface by convection, then through the wall by conduction, and finally by convection from the second wall surface to the cold fluid.

$$q = \frac{\Delta T_{overall}}{\sum R_t} = \frac{T_{\infty 1} - T_{\infty 2}}{(R_{t1,conv}) + (R_{t,cond}) + (R_{t2,conv})} = \frac{T_{\infty 1} - T_{\infty 2}}{\left(\frac{1}{h_1 A}\right) + \left(\frac{L}{kA}\right) + \left(\frac{1}{h_2 A}\right)}$$



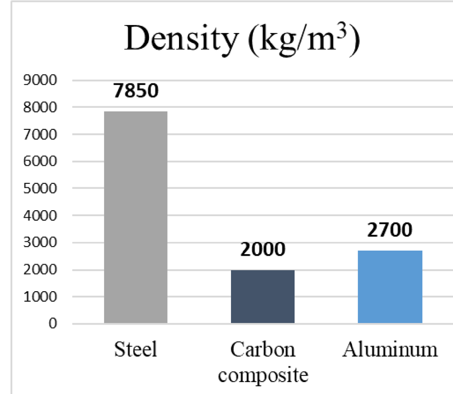
Objective

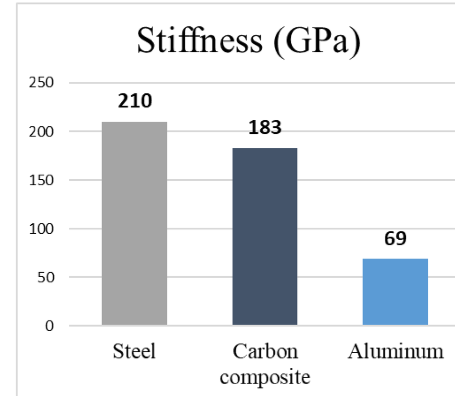
Improve the thermal management of the Li-ion battery pack of the Penn Electric Racing Car by optimizing material and design of the outer case using thermal flow simulation.

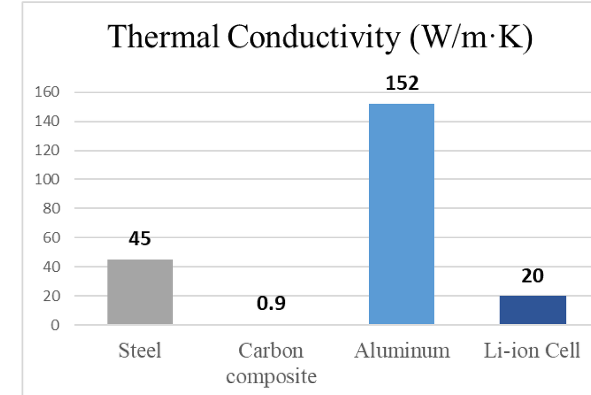
Software – SOLIDWORKS 2022

Material Properties

- Carbon composite: excellent in stiffness & density but is extremely low in thermal conductivity
- Aluminum has outstanding thermal conductivity

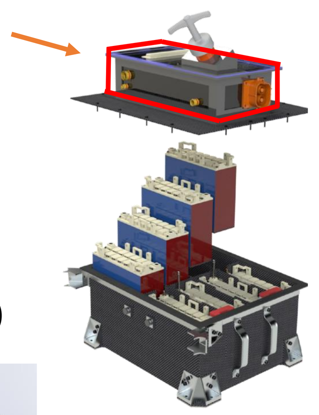


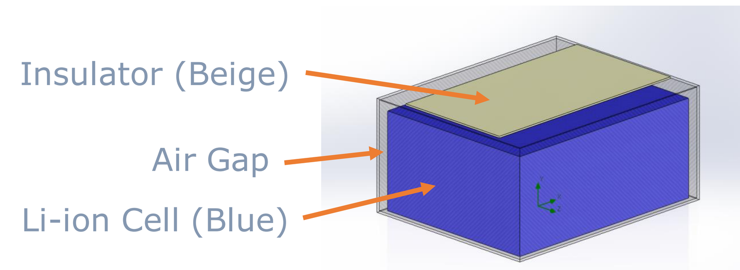




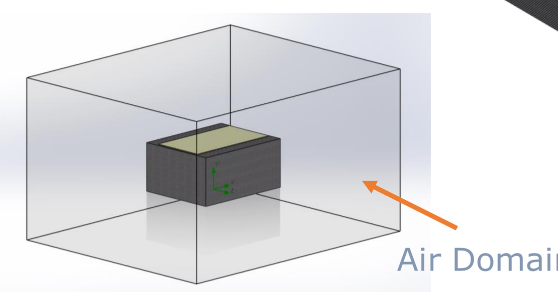
Simulation Model

- Li-ion cells and outer case are simplified for simulation
- Penthouse is modeled as a thermal insulator
- Carbon composite case: 3.0mm thickness
- Aluminum case: 2.5mm thickness (considering weight)
- Cooling fin: Oriented vertically and horizontally (same outer surface)

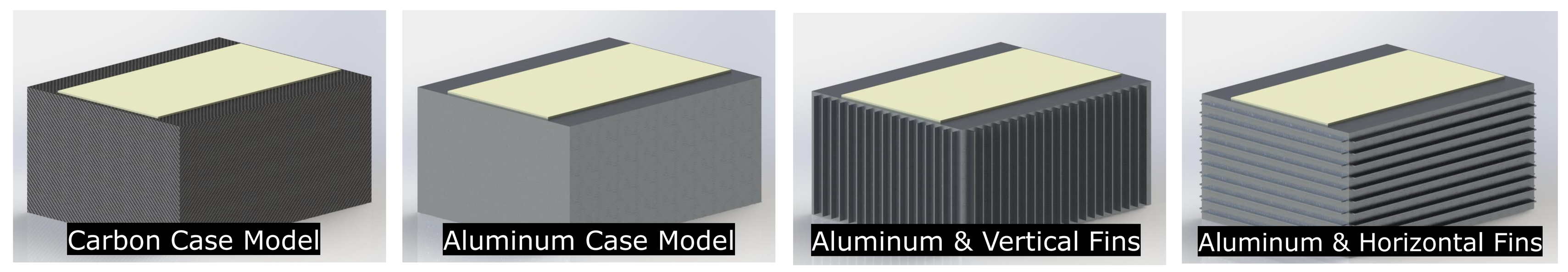




Carbon Case Model (transparent)

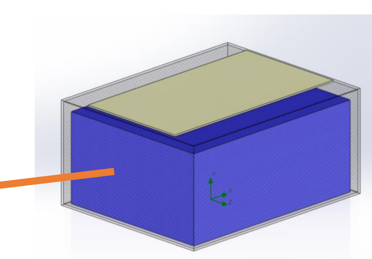


Model with Computational Domain



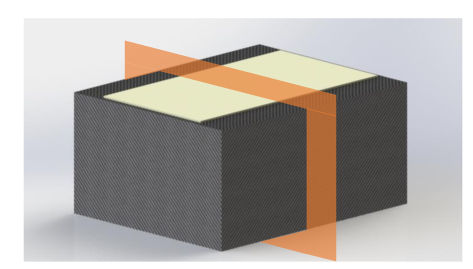
Boundary Conditions – Natural Convection

- Ambient temperature: 20°C
- Li-ion cell's heat generation: 22W
- No airflow outside the case: Natural convection

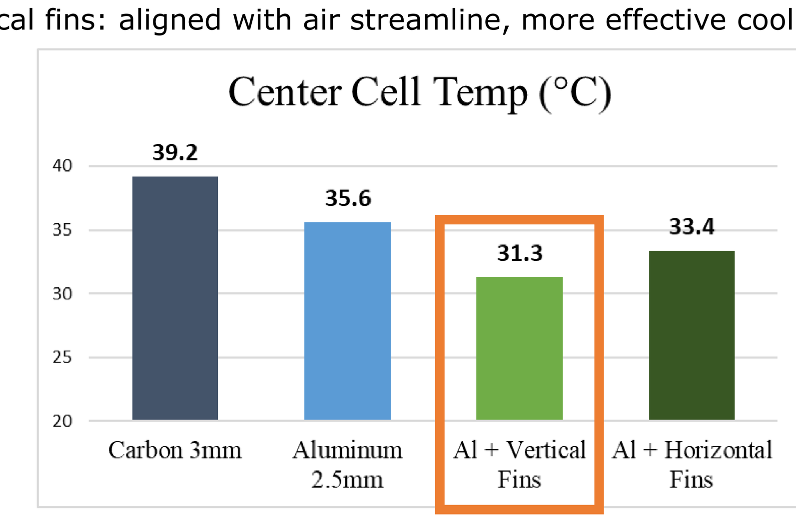


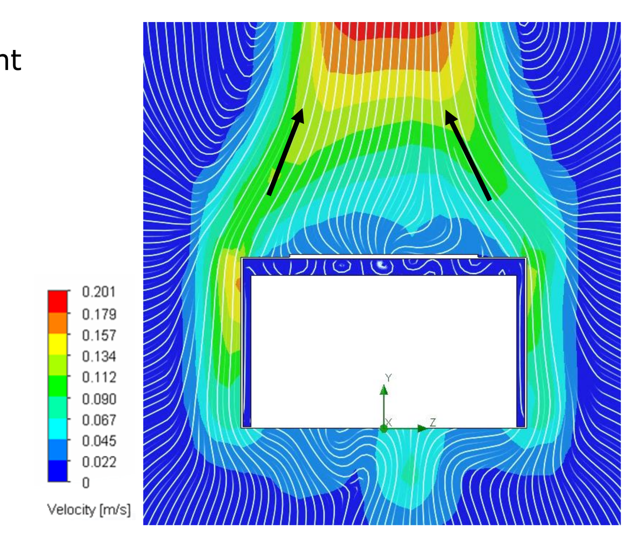
Results

- Outside air is heated and flows upward
- Carbon composite case: Cell temperature = 39.2°C
- Aluminum case: Cell temperature = 35.6°C
  - Lower temperature by higher thermal conductivity
- Cooling fin (vertical): Cell temperature = 31.3°C
  - Best cooling performance by larger outer surface exposed to ambient
  - Vertical fins: aligned with air streamline, more effective cooling

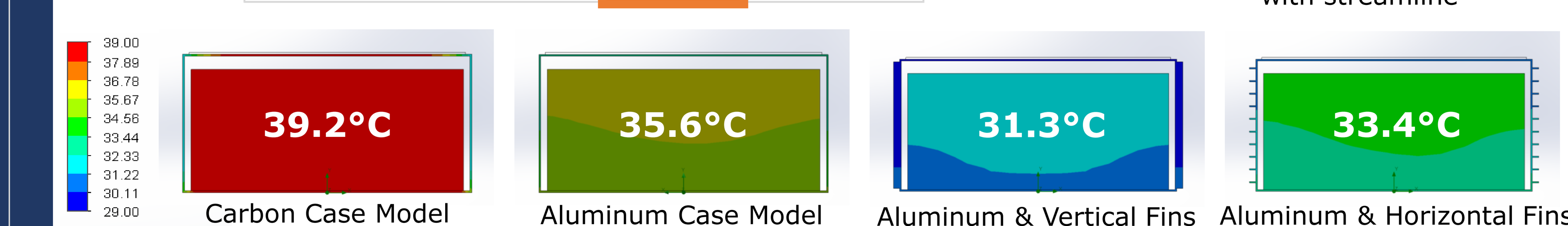


Cross Section View



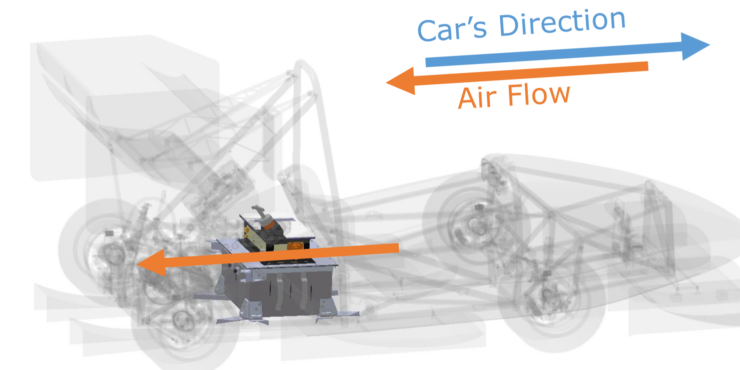


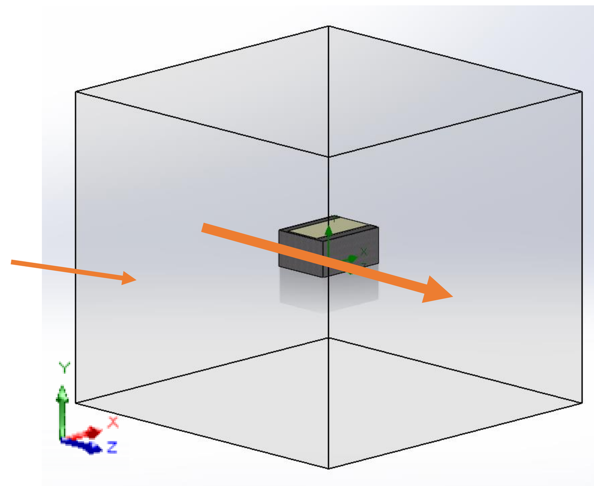
Air velocity contour with streamline



Boundary condition – Forced Convection

- Examine the effect of airflow from car movement on cell temperature
- Ambient temperature: 20°C
- Li-ion cell's heat generation: 22W
- Air flow velocity (car speed): 5km/h (3.1mi/h)

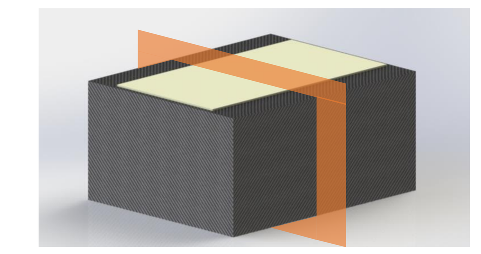




Carbon Case Model with Computational Domain
*Arrow represents the direction of the airflow

Results

- Temperature drops on all models
  - Air flow actively transfers heat from the case to the outside
- Carbon composite case: Cell temperature = 30.6°C
- Cooling fin (vertical): Cell temperature = 24.5°C
  - Best cooling performance
  - Horizontal fins: aligned with air streamline, more improvement



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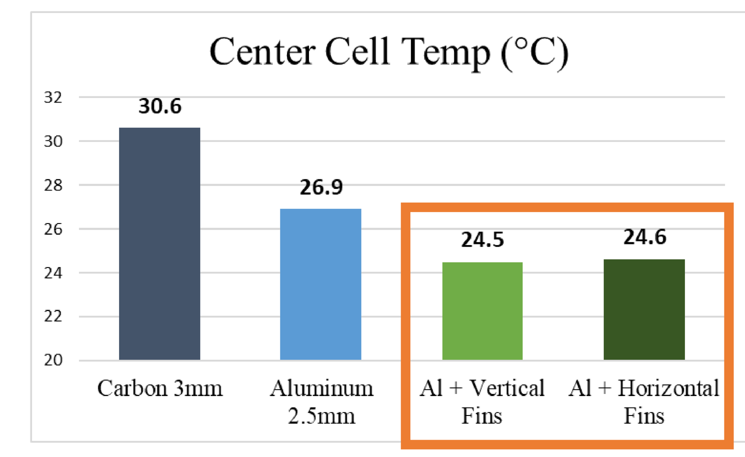

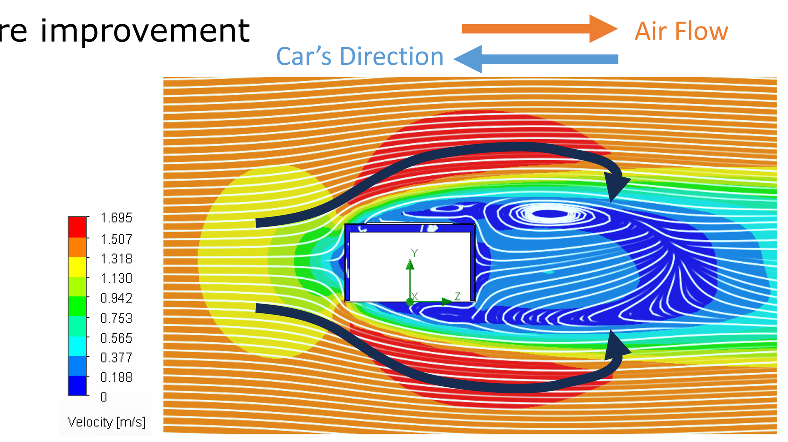

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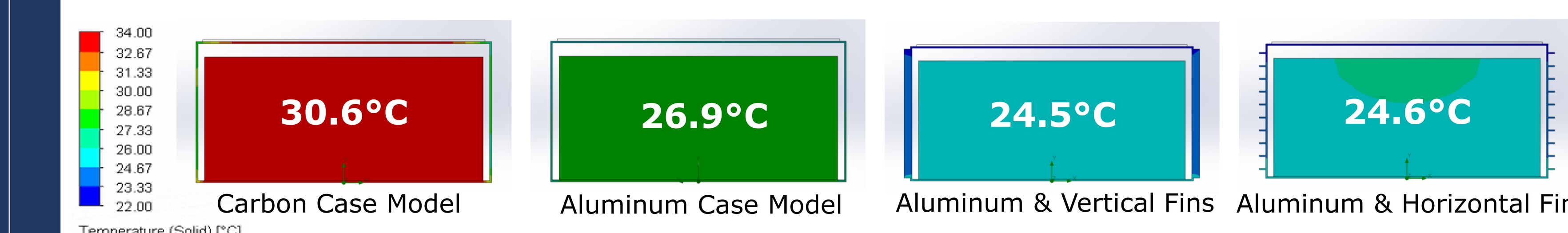
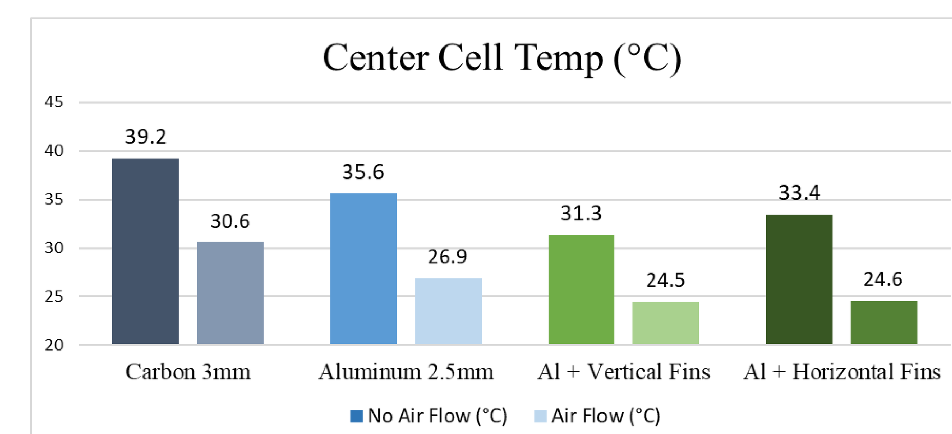
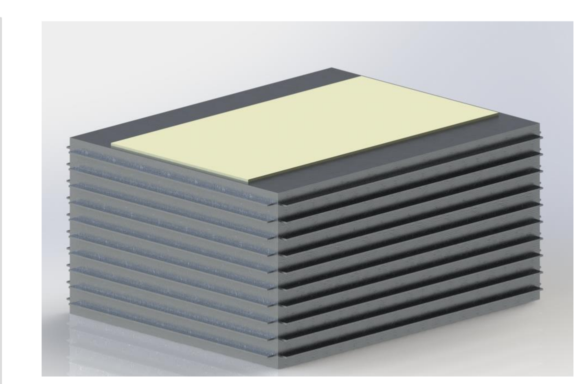


Conclusion

- Aluminum's exceptional thermal conductivity effectively dissipates heat
- The cooling fin proves highly efficient in dissipating internal heat
- Air flow around the case notably improves cooling efficiency
- Recommendation: Aluminum case with cooling fins, exposure to high airflow

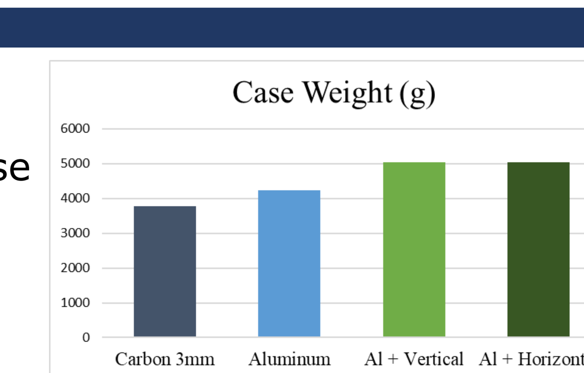




Aluminum & Horizontal Fins

Discussion

- Analysis of the total benefit considering weight increase
  - Aluminum case with cooling fins is heavier by 1.3kg
  - Aluminum's cost is competitive over carbon composite
- Actual airflow around the battery pack
  - To estimate more accurate battery pack cooling



Material 1	Carbon Composite	Aluminum	Al + Vertical Fin	Al + Horizontal Fin
Case Weight	3,767 g	4,225 g	5,046 g	5,049 g
% Carbon Weight	100	112	134	134
Cost ($)	3,000+	300	1,400	1,400