DESIGN AND SIMULATION OF LITHIUM-ION BATTERY THERMAL MANAGEMENT SYSTEM FOR MILD HYBRID VEHICLE APPLICATION

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Introduction

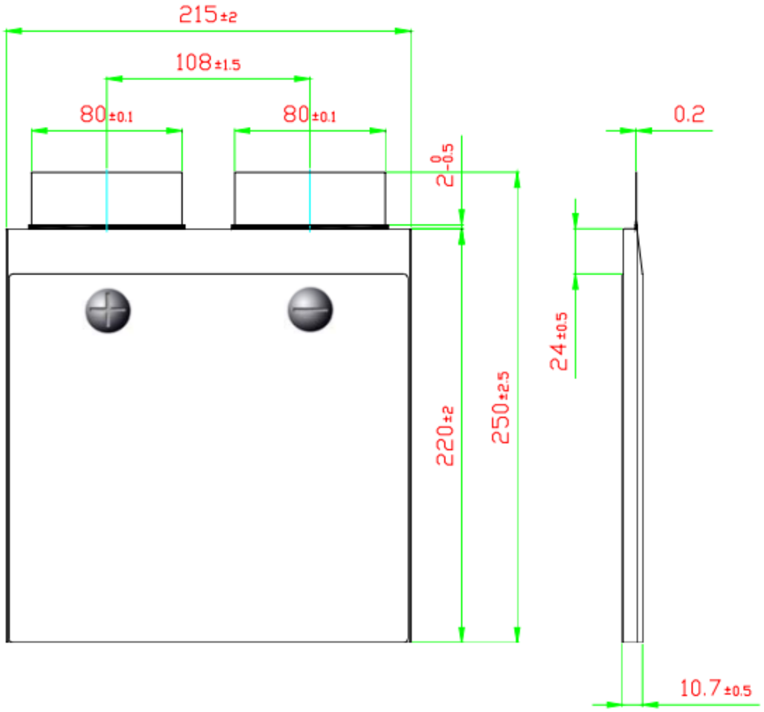
- Primary objectives of battery thermal management system
  1. (1) Limit cell temperatures below allowable maximum operating temperature,
  2. (2) Minimize cell temperature gradient, and
  3. (3) Maintain cell temperatures within the operating range for optimum performance and longevity of the battery pack.
- An air cooled Power Pack Unit (PPU) comprised of 12 series connected lithium-ion battery cells has been analyzed for a mild hybrid electric vehicle (HEV) application.
- Coupled electro-thermal modeling approach has been adopted to simulated detailed temperature distribution within the battery module and optimize air flow requirements to ensure the minimum temperature gradient.

Model development

Modeling Electrical behavior

- Battery is simulated using NTG (Newman, Tiedemann, Gu) model, which fits the open circuit voltage and discharging curves to polynomials.

Cathode	Lithium Nickel Manganese Cobalt (NMC)
Anode	Carbon
Electrolyte	Lithium Hexafluorophosphate ($LiPF_6$)
Size	220 × 215 × 10.7mm
Nominal voltage	3.7 V
Cut-off voltage	2.7 V
Discharge:	-20 °C to + 60 °C
Capacity	40 Ah
Max charge current	80A (2C)
Max discharge current	400A (10C)



Model development

NTG (Newman Tiedemann Gu) Model

$$\boldsymbol{V_{cell}(DoD, J) = -\frac{J}{Y\,(DoD)} + U_{oc}(DoD)} \qquad \boldsymbol{DoD = \frac{\int I.dt}{Capacity}} \qquad \boldsymbol{J = \frac{I}{A}}$$

First term in the right side can be considered as an ohmic term. The DoD-dependence of the parameters are expressed as polynomials

$$\boldsymbol{U_{oc} = a_0 + a_1.DoD + a_2.DoD^2 + a_3.DoD^3 + a_4.DoD^4 + a_5.DoD^5 + a_6.DoD^6}$$

$$\boldsymbol{Y = (a_7 + a_8.DoD + a_9.DoD^2 + a_{10}.DoD^3 + a_{11}.DoD^4)e^{\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}}$$

V_{cell}	cell voltage (V)
J	current density ($\mathrm{A\ m^{-2}}$)
Y	conductance ($\mathrm{S\ m^{-2}}$)
E_a	activation energy ($\mathrm{J\ mol^{-1}}$)
R	universal gas constant ($8.314472\ \mathrm{JK^{-1}mol^{-1}}$)
a_o - a_{11}	Polynomial coefficients

Model development

Heat generation rate, $\boldsymbol{Q}$ (W), can be estimated as

$$\boldsymbol{Q = I \cdot \left(U_{oc}(DoD) - V_{cell}(DoD)\right)}$$

Model calculates heat generation from the voltage profile of the fitted polynomial.

Parameter	Value	Parameter	Value
a_0 in Eq. U (V)	4.16283	a_7 in Eq. Y (A m^{-2})	673.42
a_1 in Eq. U (V)	-1.59022	a_8 in Eq. Y (A m^{-2})	-4050.34
a_2 in Eq. U (V)	8.63661	a_9 in Eq. Y (A m^{-2})	25180.7
a_3 in Eq. U (V)	-60.3325	a_{10} in Eq. Y (A m^{-2})	-58861
a_4 in Eq. U (V)	196.785	a_{11} in Eq. Y (A m^{-2})	63600
a_5 in Eq. U (V)	-319.612	E_a in Eq. Y (A m^{-2})	26009
$a_6$in Eq. U (V)	256.304		

Model development

Modeling Thermal behavior

- Battery modeling process involves running electrical and thermal solvers sequentially for each thermal time step, starting with the electrical solver.
- Electrical solver calculates electrical voltage and heat generation on a grid based on the fitted polynomial coefficients.
- Thermal solver takes the internal heat generation values, calculate the temperature field and outputs the local temperature for each thermal grid cell.
- Communication between the electrical and thermal solutions is done using internal mapping between the electrical mesh and the thermal mesh.

Model development

Modeling Thermal behavior

- The energy equation can be defined analytically as

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) + q$$

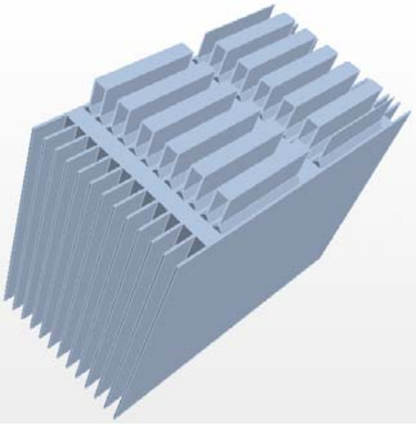
Where ρ is density $(\mathrm{kg/m^3})$, C_p is volume averaged specific heat capacity at constant pressure $(\mathrm{J/kg\text{-}K})$, T is temperature (K), k_x, k_y and k_z are effective thermal conductivity along the x, y and z directions respectively $(\mathrm{W/m\text{-}K})$, q the heat generation rate per unit volume $(\mathrm{W/m^3})$.

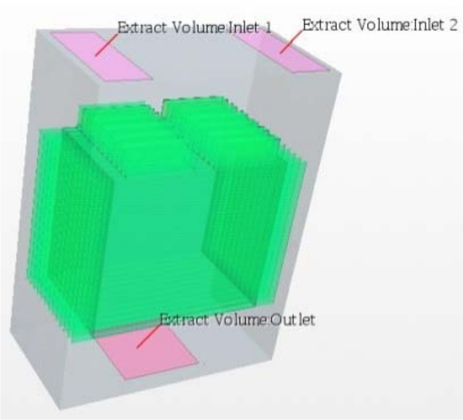
- Heat dissipation rate q_{conv} is dependent on the heat transfer coefficient h within the surrounding fluid environment. At the boundaries, this convection heat transfer rate is calculated based on local flow rate or conduction conditions.

Thermal management system design

Cool-down

- Forced air cooling system has been designed due to
  - less complexity in design,
  - low cost, weight, and
  - simpler control mechanism
- Aluminum cooling plates are sandwiched in-between the cells.
- Plates have extended surfaces for heat transfer with the flowing air.

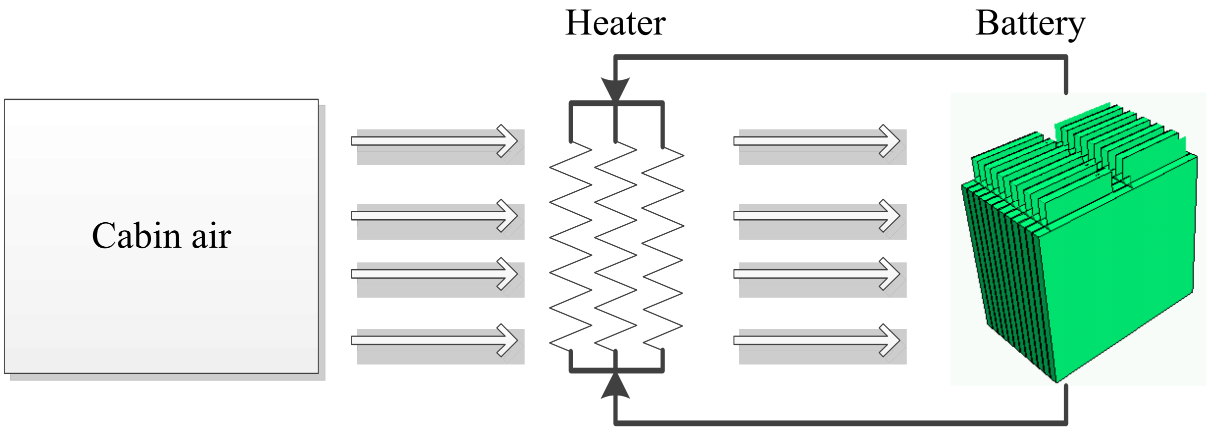




Thermal management system design

Warm-up

- During cold ambient condition, dual heating mechanism has been proposed for quick battery warm-up
  - warm cabin air used for external convective heating
  - battery internal heat generation by drawing low electrical power for a small heater to increase the inlet air further



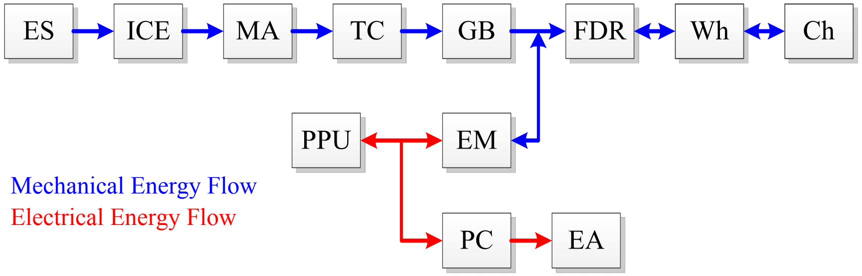
Assumptions and boundary condition

- Initial temperature of the Power Pack Unit (PPU) was assumed to be same as the drive cycle ambient condition, which is 23.89^{o}C.
- No forced air cooling was introduced until the battery maximum temperature reaches at 28^{o}C.
- US06 drive cycle was considered as the extreme driving condition/worst case
  - air condition (AC) system is inactive (OFF)
  - most aggressive one wherein harder acceleration and braking are included
  - also has the highest speed of 80 mph
- The inlet air temperature was same as ambient temperature.

Hybrid Electric Vehicle (HEV) driveline modeling

Current demand on the PPU

Current demand on a 12 cell series connected PPU for a Parallel HEV powertrain configuration has been simulated using *Autonomie* for US06 drive cycle.



ES ICE MA TC GB FDR Wh Ch

PPU EM

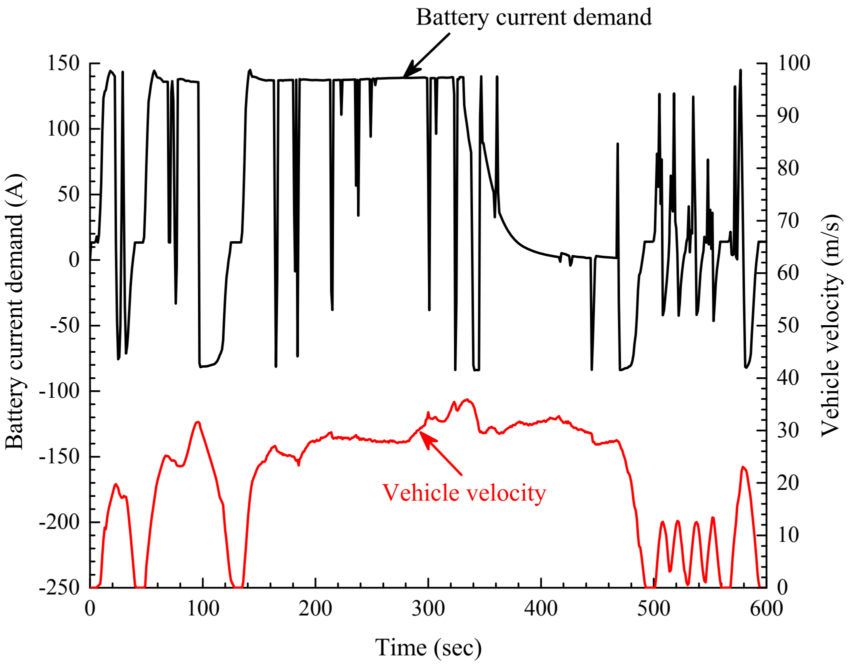
PC EA

Mechanical Energy Flow

Electrical Energy Flow

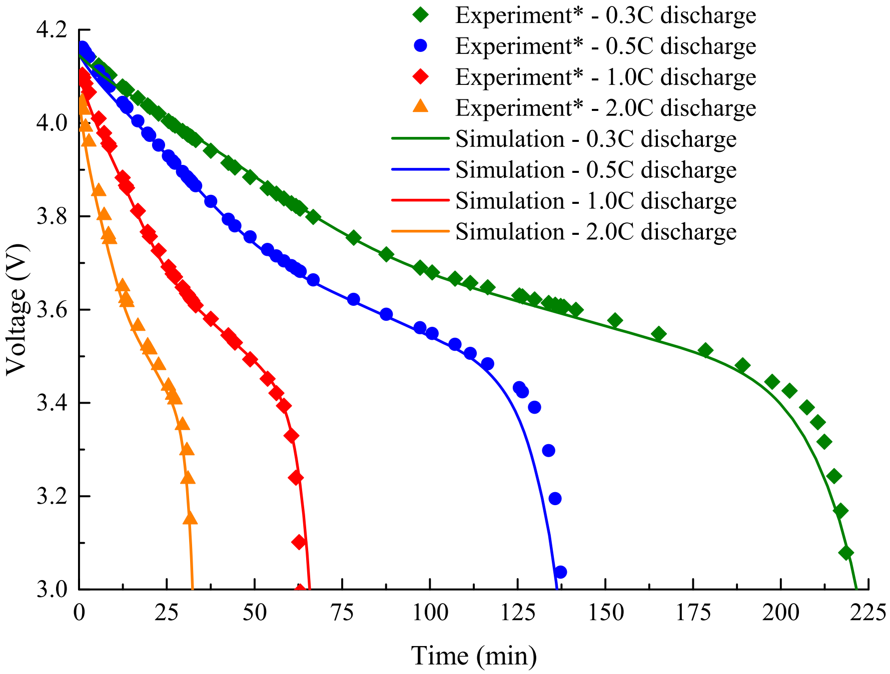
ES – Engine Starter
ICE – Internal Combustion Engine
MA – Mechanical Accessories
TC – Torque Converter
GB – Gear Box
FDR – Final Drive Ratio

PPU – Power Pack Unit
EM – Electric Motor
PC – Power Converter
EA – Electrical Accessories
Wh - Wheels
Ch - Chassis



Results and discussions

- Constant current discharge of 0.3 C, 0.5 C, 1.0 C and 2.0 C at ambient condition has been simulated and compared against the experimental data from literature.
- DoD range of 0 – 80%, all discharge curves show good match with experimental data. Maximum difference of 0.05 V was noticed for the 2.0 C discharge.

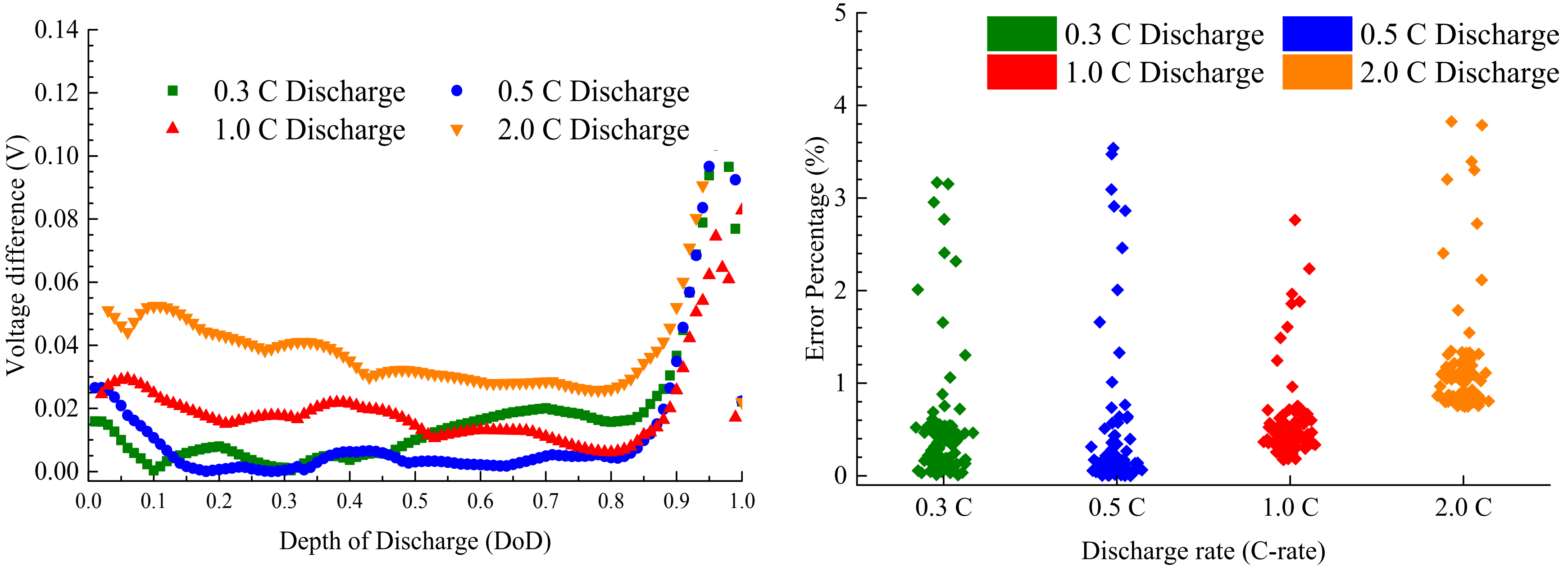


* Abdul-Quadir, Yasir, Tomi Laurila, Juha Karppinen, Kirsi Jalkanen, Kai Vuorilehto, Lasse Skogström, and Mervi Paulasto-Kröckel. "Heat generation in high power prismatic Li-ion battery cell with LiMnNiCoO2 cathode material." *International Journal of Energy Research* 38, no. 11 (2014): 1424-1437

Results and discussions

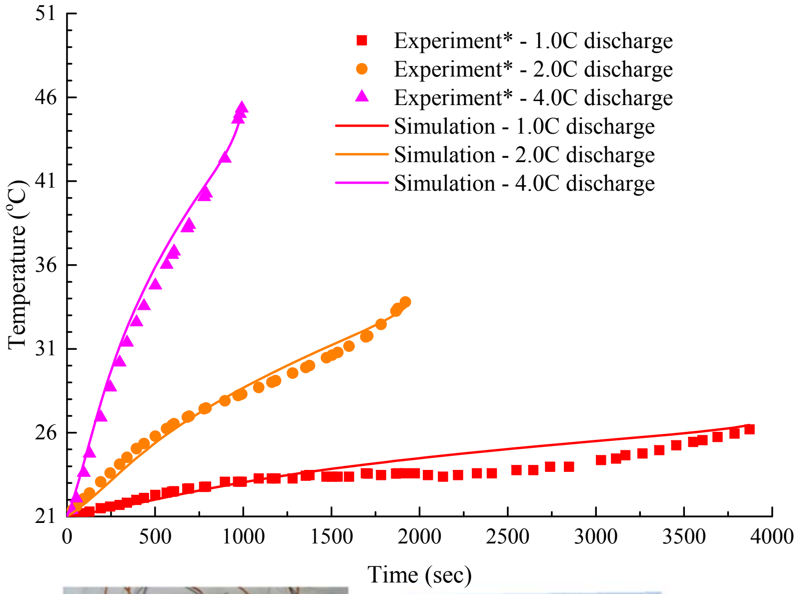
- Voltage difference starts to increase towards the end of the discharge (after 80% DoD) and reaches up to 0.1V. Maximum error was found to be less than 4%.

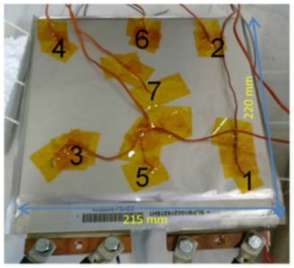
$$Percentage\ Error_{(at\ a\ specific\ DoD)} = \frac{V_{Exp} - V_{sim}}{V_{Exp}}\ x\ 100$$

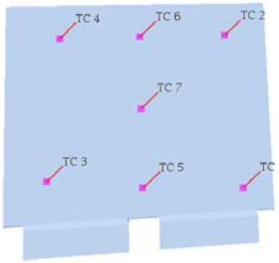


Results and discussions

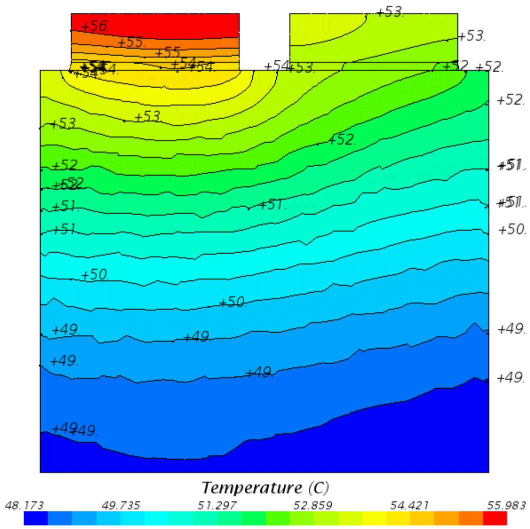
- Cell temperature rise was simulated for various constant current discharge cases 1.0 C, 2.0 C & 4.0 C.





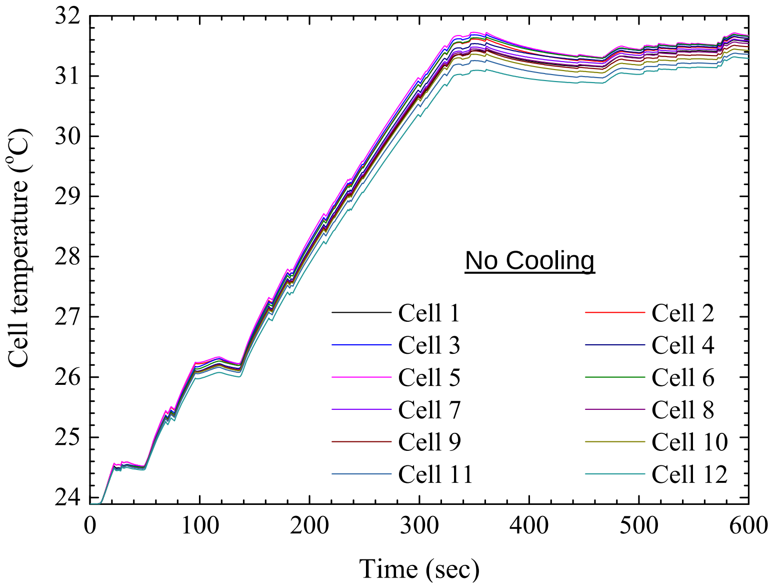


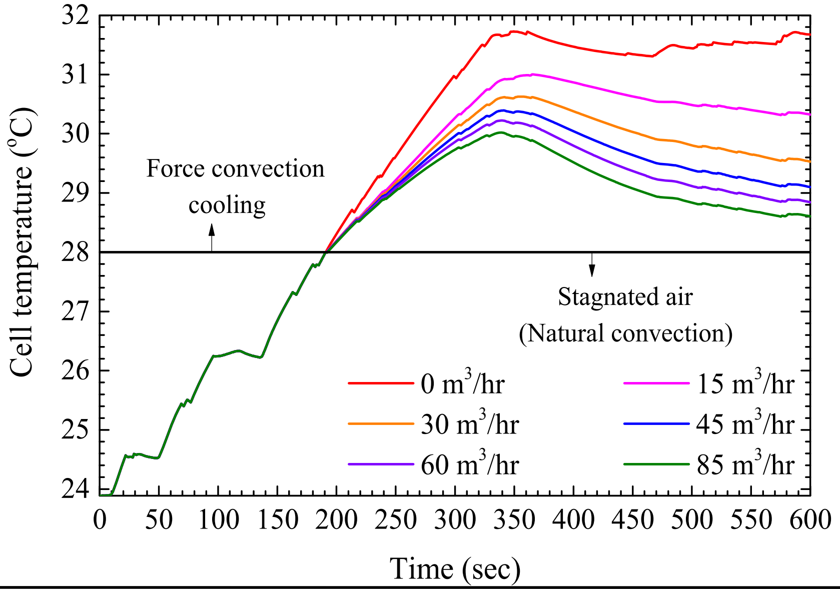
- Temperature distribution on the cell surface was simulated for 5.0 C discharge to evaluate the gradient.
- End of 5.0 C discharge, maximum temperature gradient was found to be 5^{o}C, positive tab being the hottest spot



Results and discussions

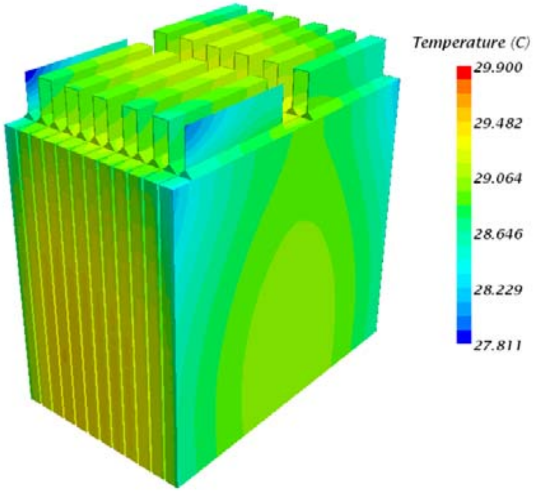
- Without having any airflow for cooling, the maximum cell temperature can go up to 31.8^{o}C during US06 drive cycle (after 340 sec of the cycle)
- Various simulation was ran to optimize the airflow requirement for maintaining the maximum cell temperature below 30^{o}C. Force convection has been introduced when the battery temperature reaches at 28^{o}C.

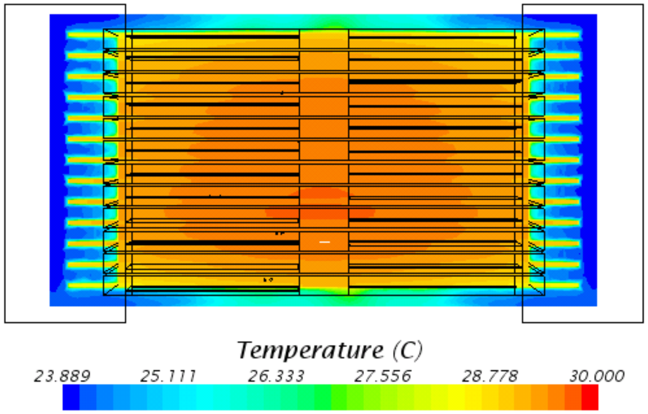


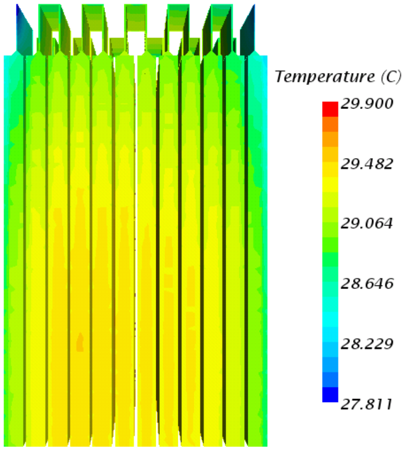


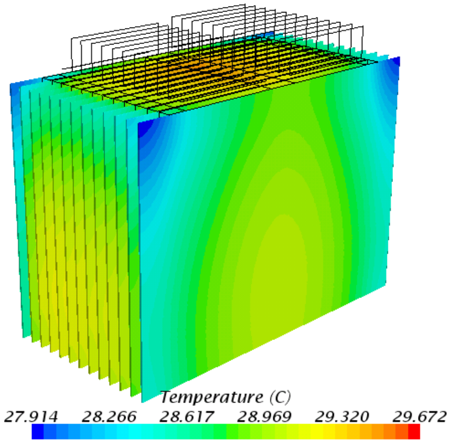
Results and discussions

- Detailed temperature distribution on the cells and the cooling plates show temperature uniformity within the PPU.
- Maximum temperature gradient of 1.4^{o}C was found within the cells during US06 drive cycle (at 340 seconds) for airflow rate of $85\ \mathrm{m^3/h}$.









Conclusion

- Coupled 3-D electro-thermal Computational Fluid Dynamics (CFD) analysis was done on a 12 cell series connected Power pack Unit (PPU) for mild HEV application to optimize the air flow requirement for minimizing the temperature gradient within the module.
- Proposed design comprised of 1.5mm thick aluminum plates sandwiched between the adjacent cells and having 26mm extended surface area on both sides as fins requires minimum airflow rate of $85\ \text{m}^3/\text{h}$ to meet the functional objective.
- Transient analysis for US06 dynamic drive cycle using NTG battery model approach provides us the detail temperature distribution within the PPU unit and can be useful for the “off-line” control calibration.

Future recommendations

- Model accuracy can be improved by adopting high fidelity detailed electrochemical modeling approach, which can predict electrochemical and thermal parameters more accurately.
- Thermal management system can be designed and optimized more efficiently by running Design of Experiment (DoE) while considering more variable parameters.

Acknowledgement

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<u>**Thank You!**</u>

Questions?