

Battery Thermal Management System Design Modeling

Gi-Heon Kim, Ph.D

Ahmad Pesaran, Ph.D (ahmad_pesaran@nrel.gov)

National Renewable Energy Laboratory, Golden, Colorado, U.S.A.



With support from

High Power Energy Storage Program (Tien Duong and Dave Howell)

Office of FreedomCAR and Vehicle Technologies

Energy Efficiency and Renewable Energy Office

U.S. Department of Energy



Motivations & Objectives

Motivations

- Battery thermal management is critical in achieving **performance** and extended **life** of batteries in electric and hybrid vehicles.
- Appropriate models that can predict thermal behaviors of batteries shorten the development process for improving battery system design.

Objectives of this Study

- To investigate the impact of cooling strategies with different coolant systems; air and direct/indirect liquid cooling
- To evaluate system thermal responses and their sensitivities as a function of controllable system parameters
- To provide battery thermal management system design insight by identifying analyses and approaches that engineers should consider when they design a battery thermal management system for electric and hybrid vehicles

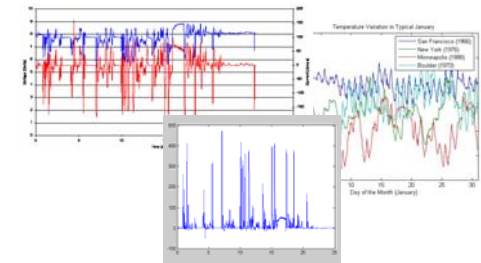
Cell Characteristics

- Shape: Prismatic/Cylinder/Oval etc
- Materials/Chemistries
- Size/Dimensions/Capacity
- Thermal/Current Paths inside a Cell



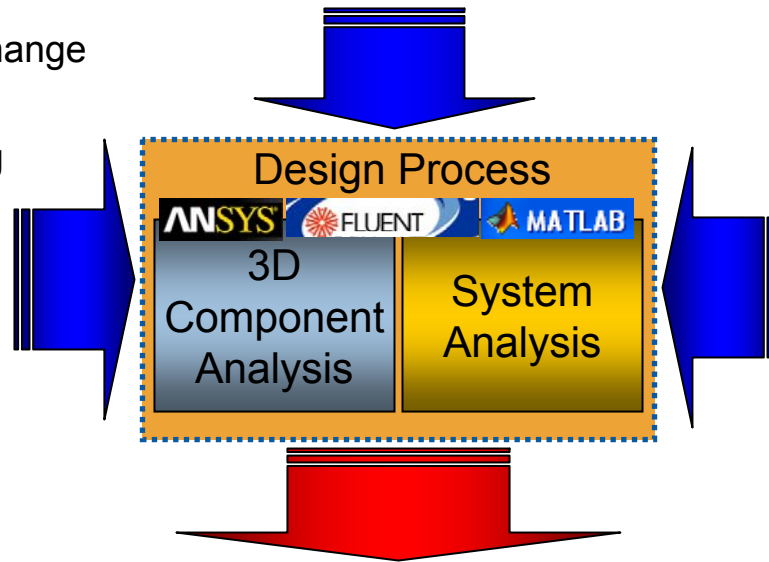
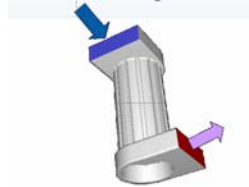
Operating Conditions

- Vehicle Driving Cycles
- Control Strategy
- Ambient Temperature
- etc



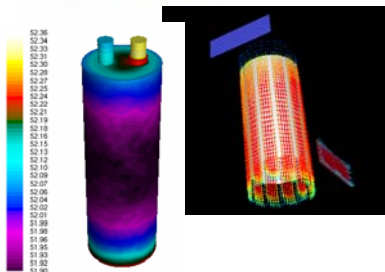
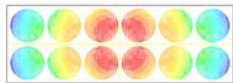
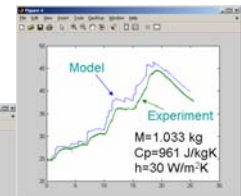
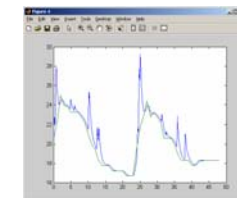
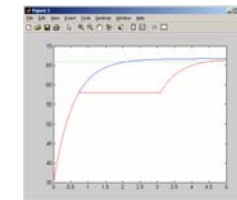
Module Cooling Strategy

- Passive control with phase change
- Coolant type: Air/Liquid
- Direct Contact/Jacket Cooling
- Serial/Parallel Cooling
- Terminal/Side Cooling
- Module Shape/Dimensions
- Coolant Path inside a Module
- Coolant Flow Rate
- etc



Battery Thermal Responses

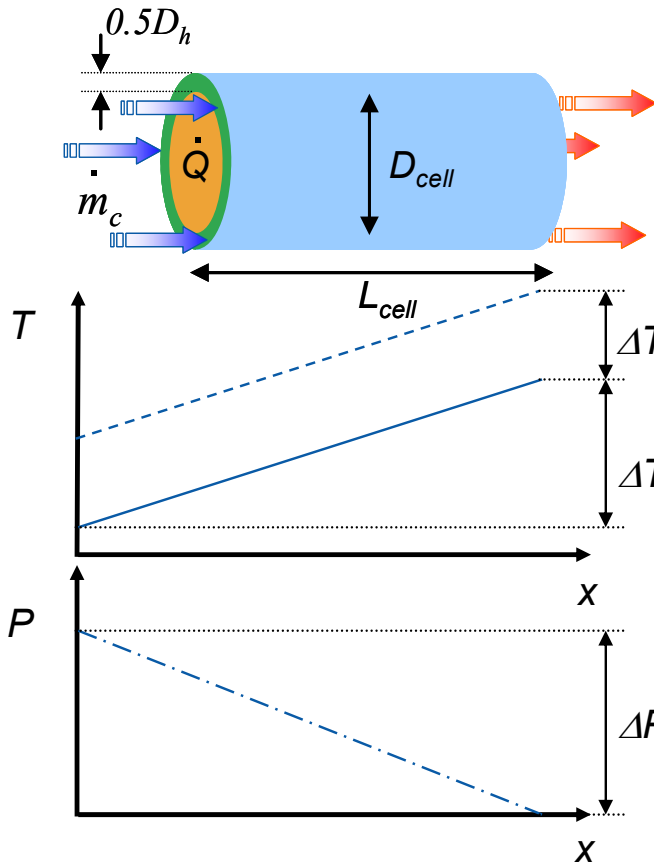
- Temperature History Cells/Module/Pack
- Temperature Distribution in a Cell
- Cell-to-Cell Temperature Imbalance in a Module
- Battery Performance Prediction
- Pressure Prop and Parasitic Power
- etc.



Approach

- NREL has developed a 3-D electro-thermal model to predict thermal response of real cells – focus on cell internal temperature (EVS-21)
- In this study, focus is mostly external to cell – fluid side
 - Air cooling
 - Liquid cooling
 - Direct
 - Indirect
- The battery management system response were evaluated using
 - Fully developed laminar channel flow analysis
 - Computational Fluid Dynamic (CFD) analysis
- The system responses oof interest were
 - Coolant temperature change (outlet - inlet)
 - Temperature difference between cell surface and bulk coolant
 - Pressure drop in coolant channel (fluid power requirements)

Typical Parallel Cooling Analysis (all the cells are treated the same)



- - - - - cell surface temperature
 ———— coolant mean temperature
 - · - · - pressure

Cell Specifics

- Dimensions
- Heat Generation

Heat Transfer Fluid Properties

- Density
- Specific Heat
- Thermal Conductivity
- Viscosity

Control Parameters

- Coolant Mass-flow Rate (m_c)
- Coolant Channel Dimension (D_h)

System Responses of Interest

- ΔP : Channel Pressure Loss
- ΔT_1 : Coolant Temperature Change
- ΔT_2 : Coolant-Cell Temperature Difference

Fully Developed Laminar Flow Analysis Annular Channel Cooling

If coolant channel gap is small enough compared with cell diameter,

$$c_f Re = 24$$

$$Nu = 5.385$$

where, $Re = \frac{VD_h}{\nu}$, $Nu = \frac{hD_h}{k}$

hydraulic diameter

$$D_h = 4 A_c / p$$

where

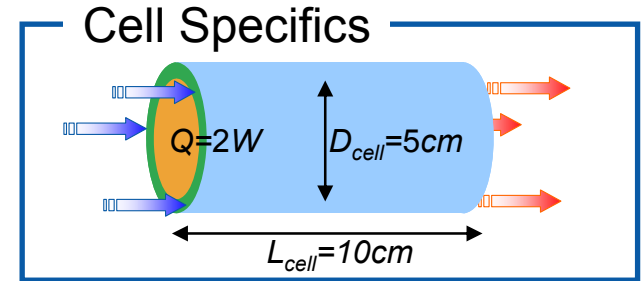
A_c : area section of the channel
 p : perimeter of the channel

mean velocity

$$V = \dot{m} / (\rho A_c)$$

where

ρ : coolant density
 \dot{m} : coolant mass flow rate



Heat Transfer Fluid Specifics

	Air	Mineral Oil	Water/Glycol
ρ (g/m ³)	1.225	924.1	1069
c_p (J/kg K)	1006.43	1900	3323
k (W/m K)	0.0242	0.13	0.3892
ν (m ² /s)	1.4607e-5	5.6e-5	2.582e-6

System Responses

$$\Delta P = 4 \tau_o L / D_h \quad \Delta T_1 = Q / (\dot{m} c_p) \quad \Delta T_2 = Q / (\pi D_{cell} L h)$$

Control Parameters

\dot{m} : Coolant Mass Flow Rate

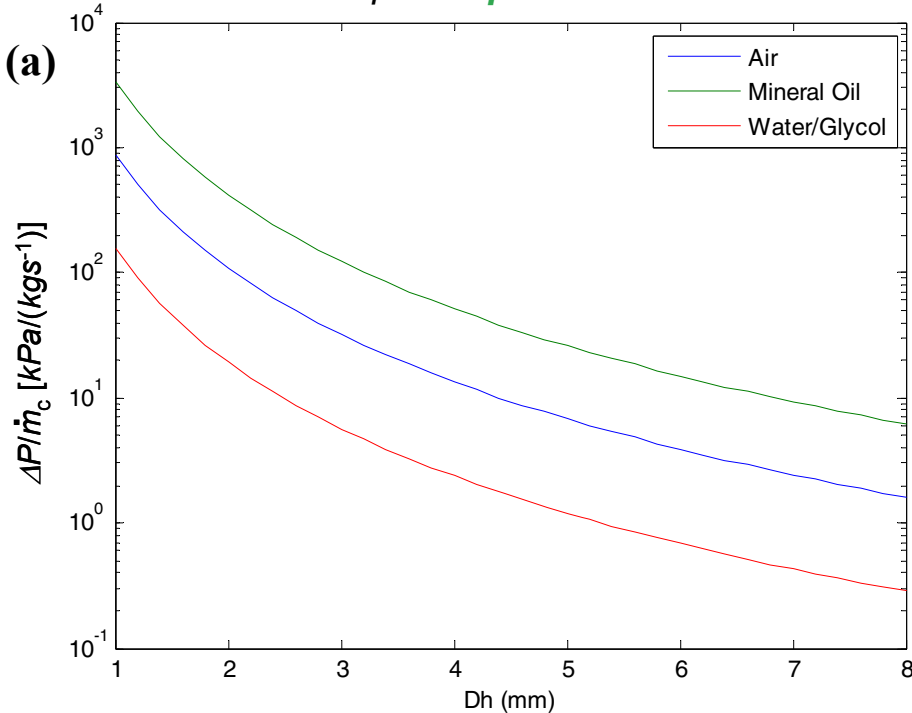
D_h : Hydraulic Diameter of Coolant Channel

Channel Pressure Loss ΔP

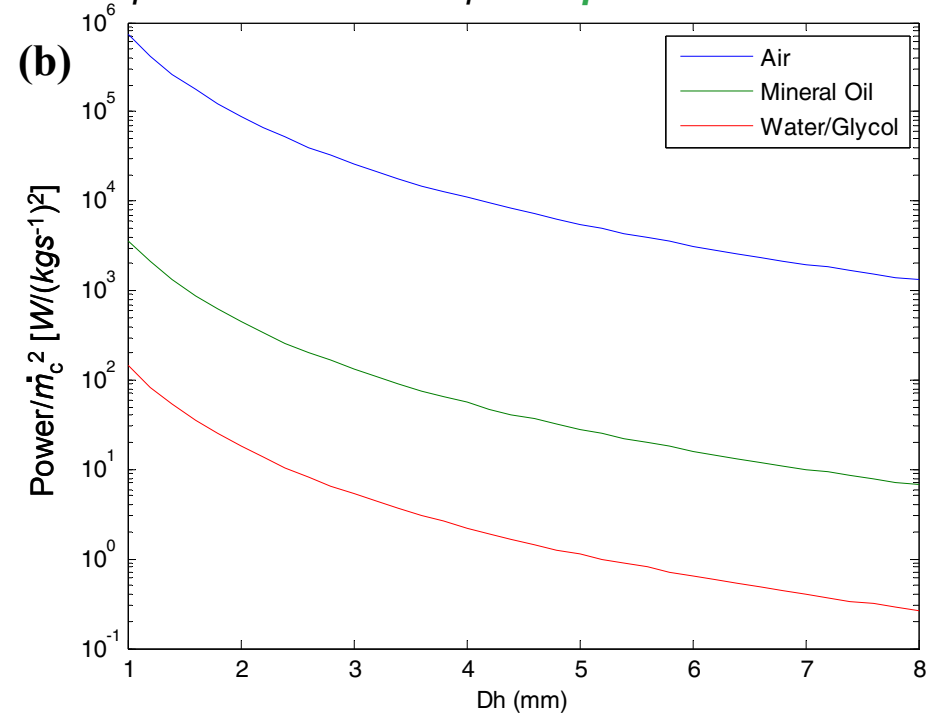
$$\Delta P \sim \frac{\dot{m}_c v}{D_h^3}$$

$$\frac{\partial \Delta P}{\partial D_h} \sim -\frac{\dot{m}_c v}{D_h^4}$$

Mass-rate specific **pressure**



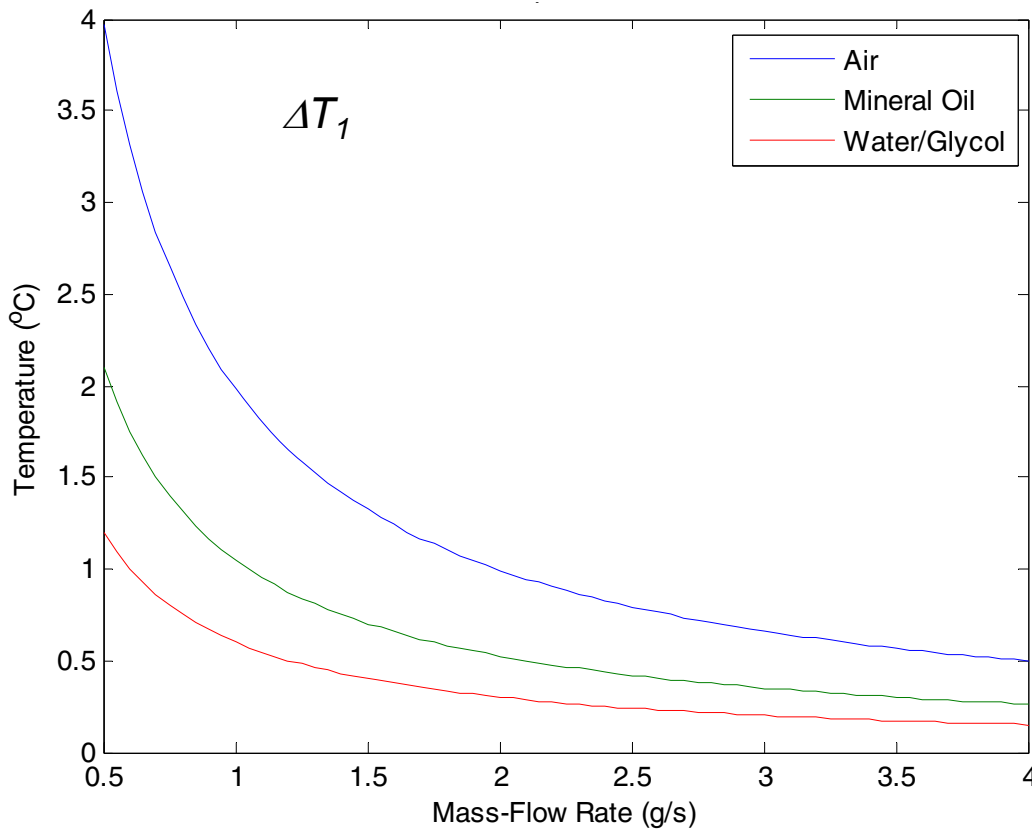
Square-of-mass-rate specific **power**



- Large difference in kinematic viscosity \rightarrow , ΔP varies in very different ranges
- ΔP inversely proportional to D_h^3 at $D_{cell} \gg D_h$ and laminar flow
- The channel pressure loss changes are very sensitive to D_h when it is small.
- Due to the much smaller fluid density and consequently larger volumetric flow rate at given mass flow rate, the air cooling system requires much higher flow power

$$W_f \sim \frac{\dot{m}_c^2 v}{\rho D_h^3}$$

Coolant Temperature Increase ΔT_1

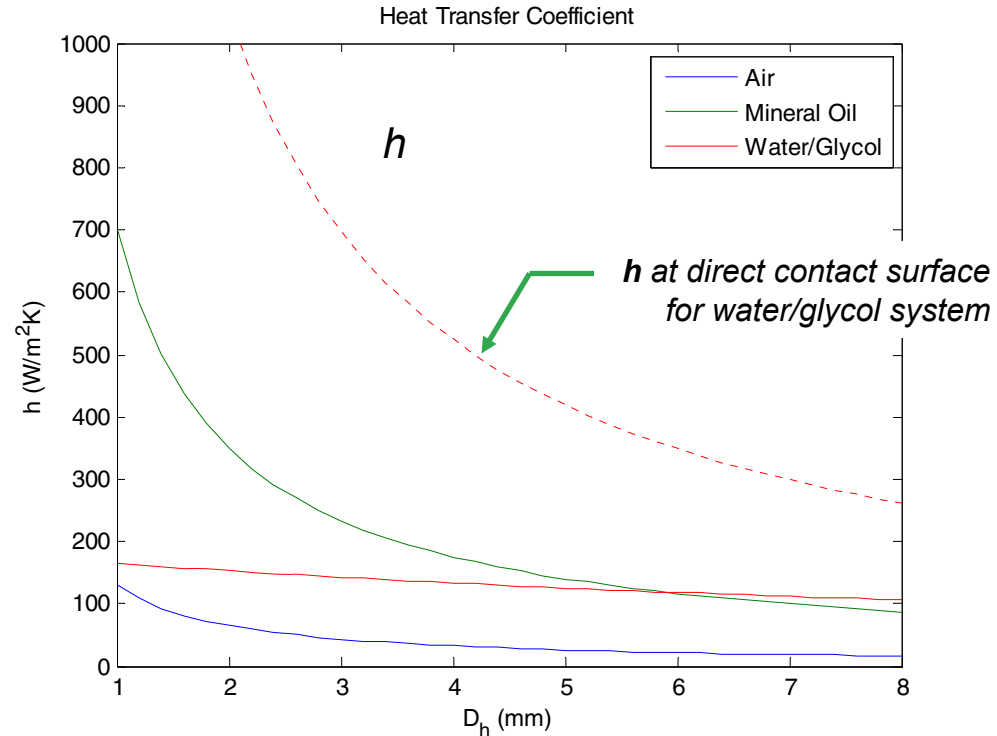
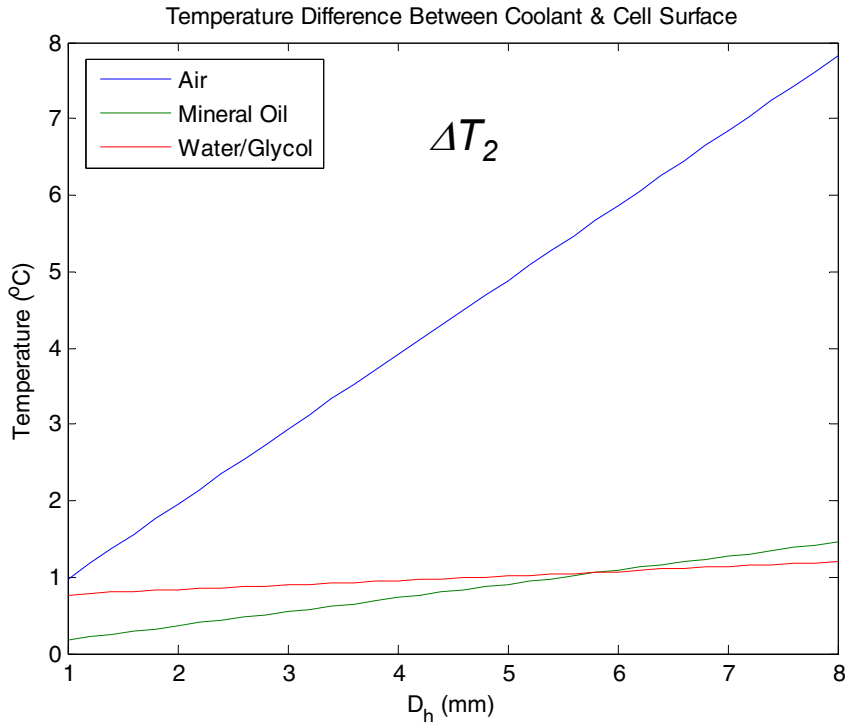


- To achieve the temperature uniformity over a cell, it is preferred to keep coolant temperature change in the channel as small as possible.
- ΔT_1 is inversely proportional to coolant heat capacity flow rate.
- Therefore, increasing mass flow rate is not as effective for reducing coolant temperature change in large flow rate cooling as it is in a small flow rate cooling.
- A little change of flow rate can greatly affect the coolant temperature change and consequently cell temperatures at small coolant flow rate (especially for air system having small c_p).

$$\Delta T_1 \sim \frac{1}{\dot{m}_c c_p} \quad \frac{\partial \Delta T_1}{\partial \dot{m}} \sim -\frac{1}{c_p} \frac{1}{\dot{m}_c^2}$$

Temperature Difference between Coolant Bulk and Cell Surface

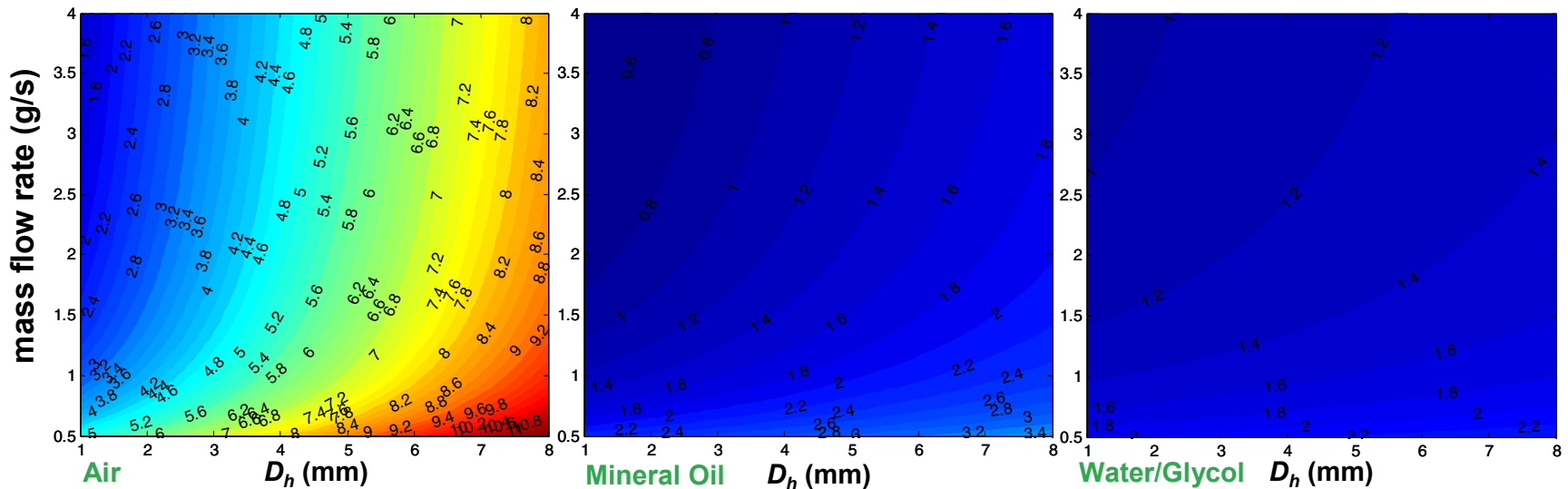
$$\Delta T_2$$



- ΔT_2 varies linearly with D_h with slope being proportional to $1/k$.
- ΔT_2 rapidly increases with D_h in air cooling due to its small thermal conductivity.
- The heat transfer coefficient (h) evaluated at cell surface for water/glycol jacket cooling is greatly reduced and not sensitive to channel height due to added thermal resistances between coolant and cell surface.
- High h system reduces ΔT_2 , and removes heat fast from small temperature difference.

Maximum Cell Surface Temperature relative to Coolant Inlet

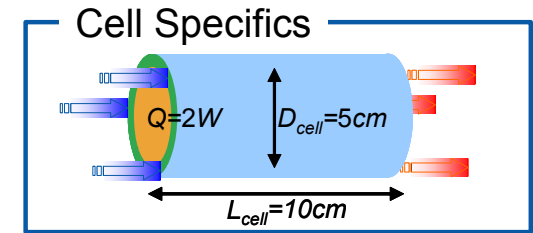
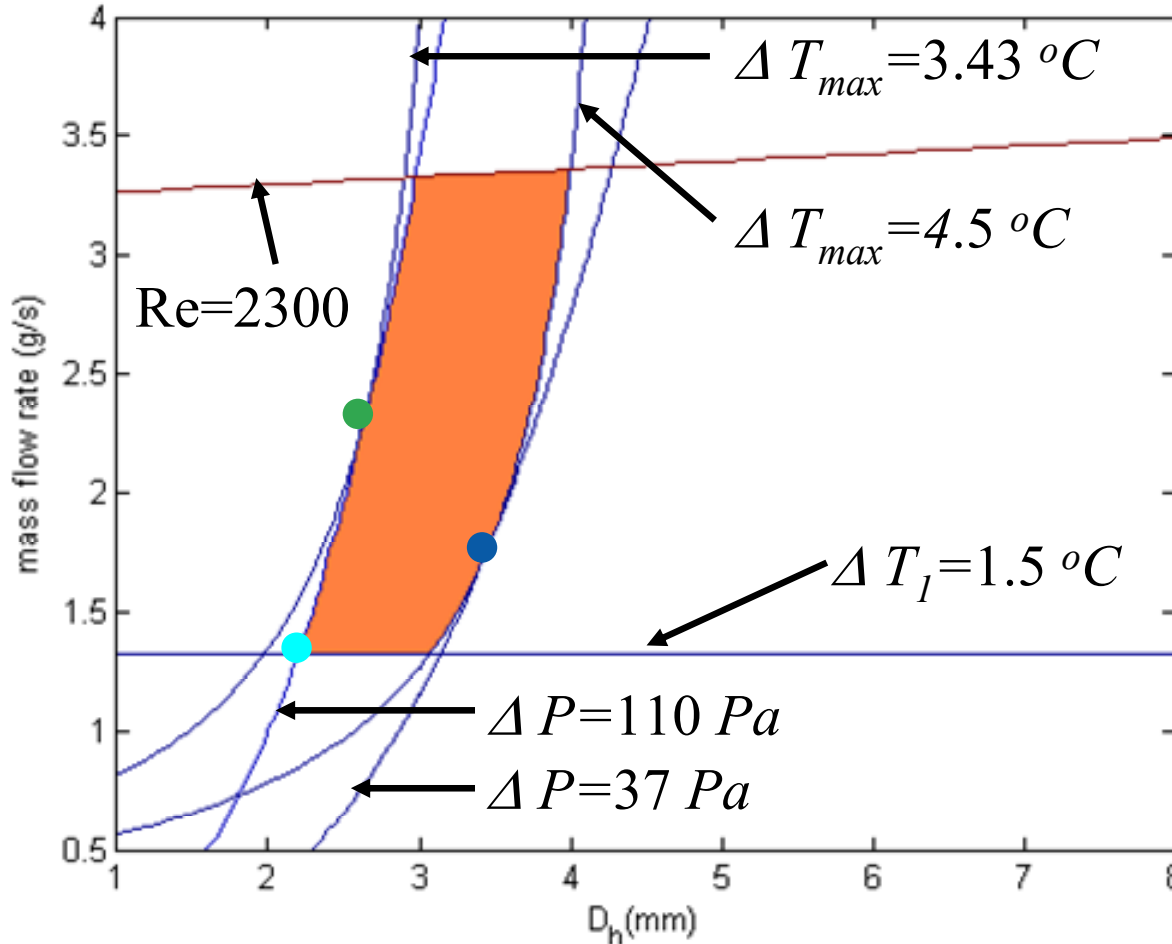
$$\Delta T_{max} (= \Delta T_1 + \Delta T_2)$$



- ΔT_{max} in the air system are much higher compared with other fluid systems due to its small heat capacity and thermal conductivity.
- The air system: ΔT_{max} is dominated by and sensitive to D_h .
- The water/glycol jacket cooling system: ΔT_{max} is not very sensitive to D_h , and ΔT_{max} is not a strict limiting thermal design factor in a water/glycol system.

Optimizing Operation Parameters

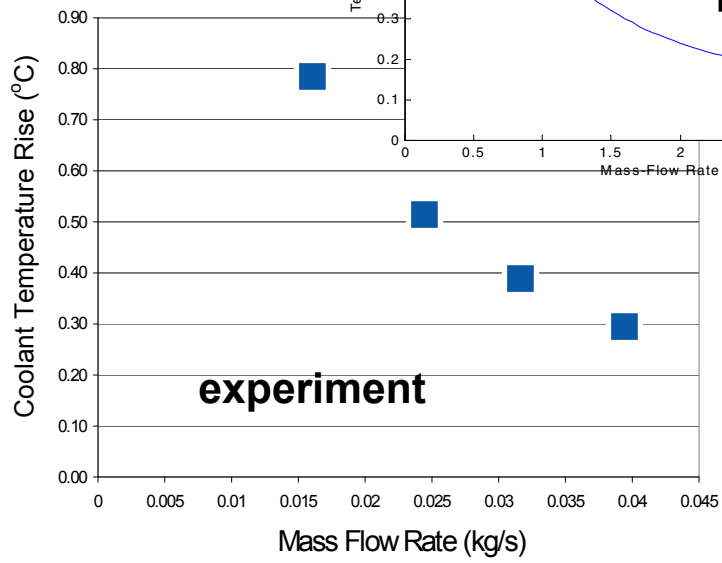
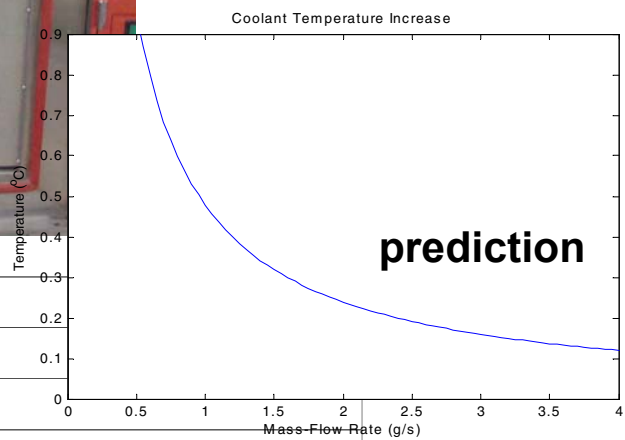
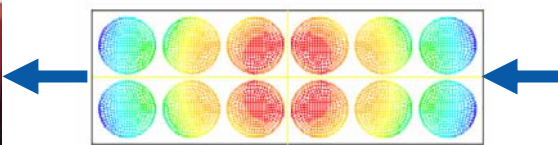
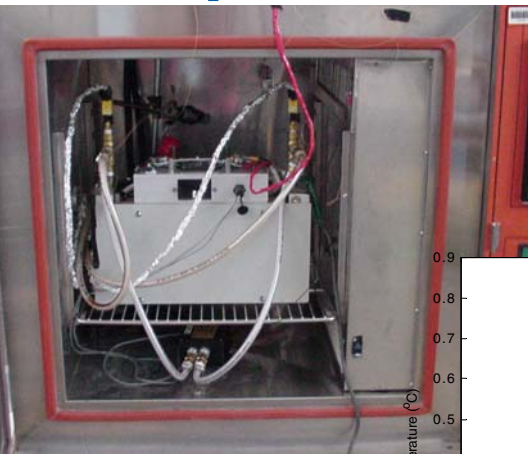
- Air Cooling System



- Confining Factors
- Colored Zone satisfies
 - $Re < 2300$
 - $\Delta P < 110 Pa$
 - $\Delta T_1 + \Delta T_2 < 4.5^\circ C$
 - $\Delta T_1 < 1.5^\circ C$

- : maximum *heat transfer coefficient* (h) operating point
- : lowest *max temperature* ($\Delta T_1 + \Delta T_2$) operating point
- : minimum *pressure loss* (ΔP) operating point

Trend Validation: Module Liquid Cooling Experiment



Tested Module Cooling System

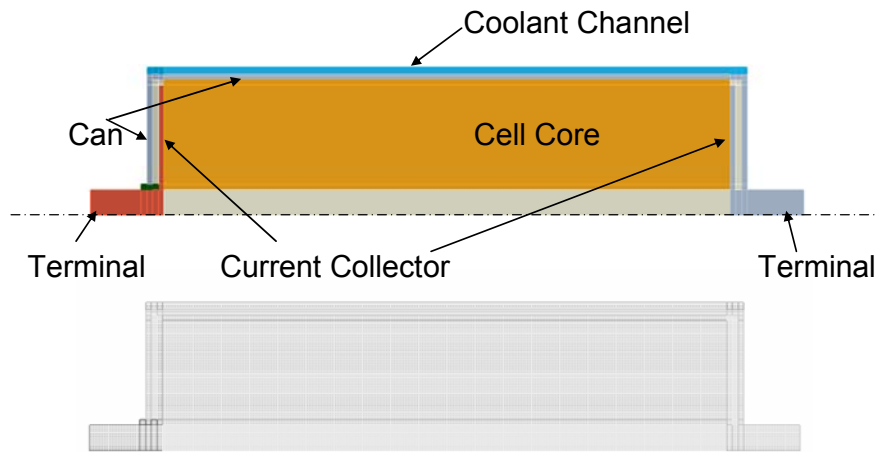
- 12 li-ion cylindrical cells
 - Indirect jacket cooling
 - Coolant channels not completely fully developed
 - Discharged at constant C rate
-
- Coolant (water) temperature increase is inversely proportional to the coolant mass flow rate.
 - Coolant temperature change at high mass flow rates is not as sensitive to mass flow rate as it is at low mass flow rates.
 - Note that the magnitude of coolant temperature change at given heat removal rate is relatively small due to large heat capacity of water/glycol.

Computational Fluid Dynamic (CFD) Evaluation

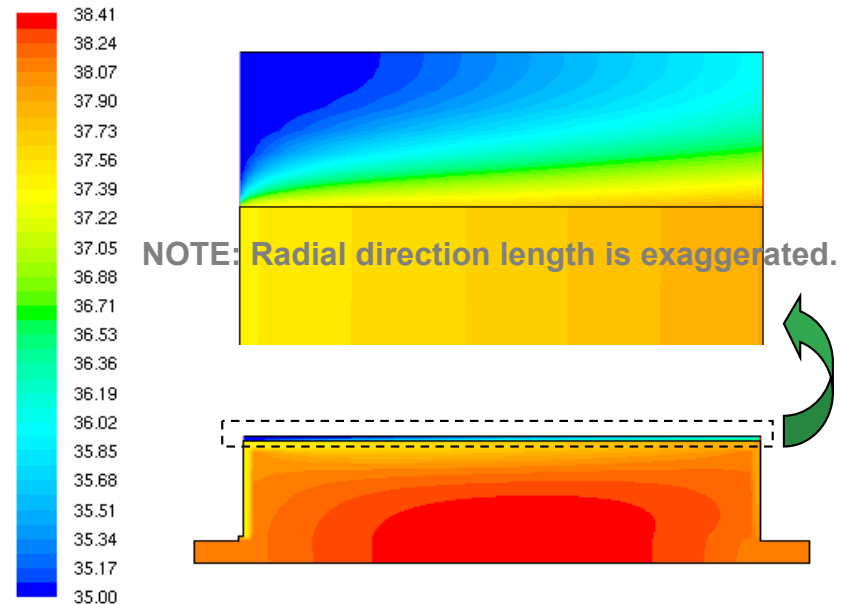
Direct Air Cooling

- ✓ Heat Generation: 2 W per Cell
- ✓ Channel Inlet Air Temperature: 35°C
- ✓ Air Mass Flow Rate: 1.33 g/s per Cell
- ✓ Channel Gap Height: 1.1 mm ($D_h = 2.2$ mm)

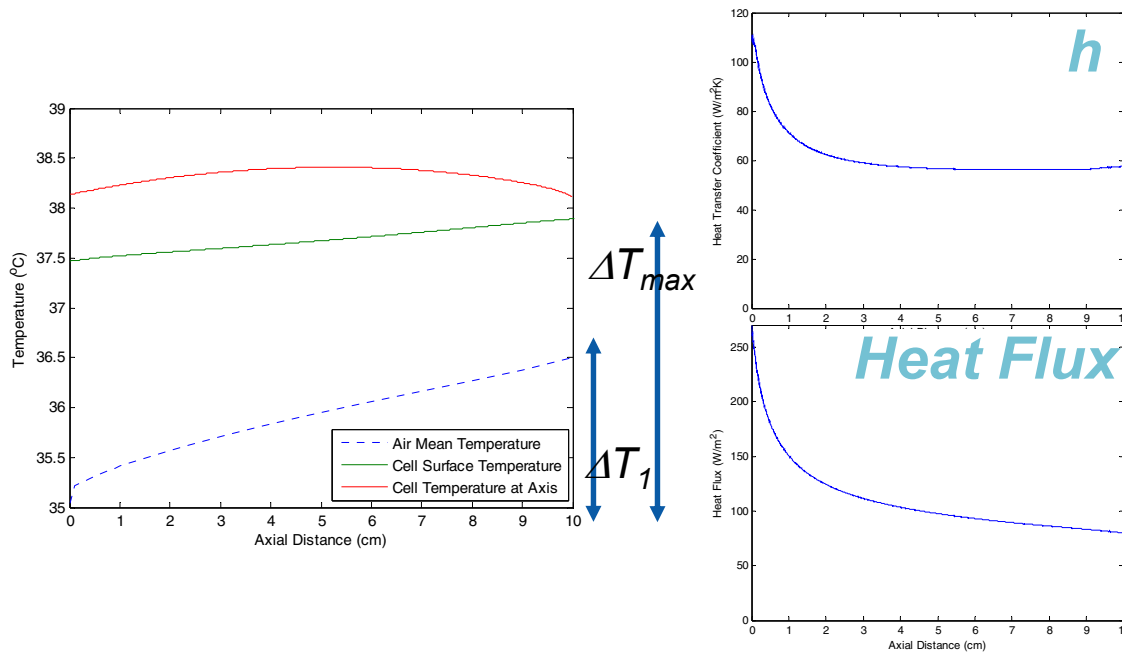
Geometry & Mesh



Temperature Distribution



CFD Predictions: Temperatures, h and Surface Heat Flux Profiles



ΔT_{max} Disagreement

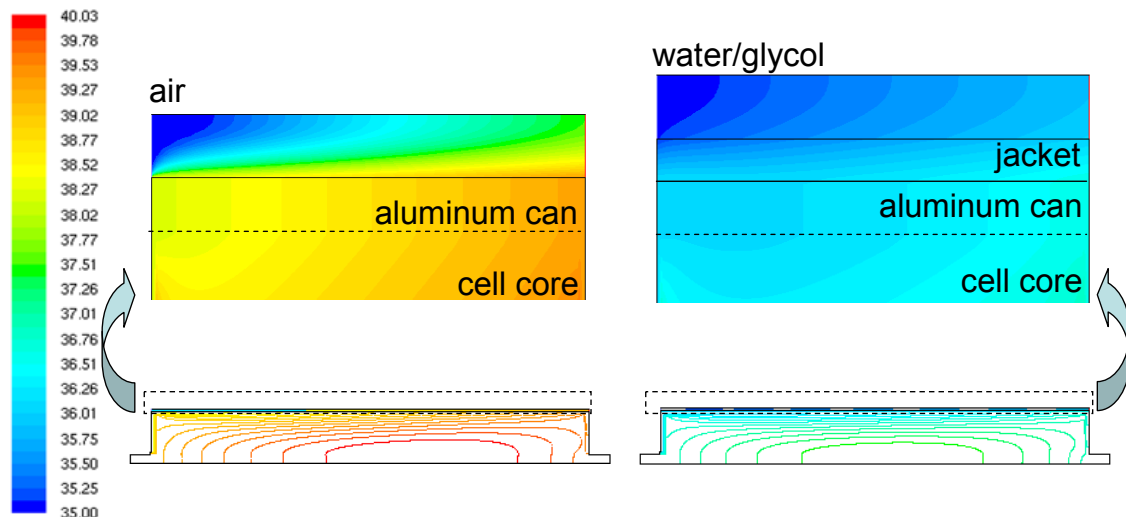
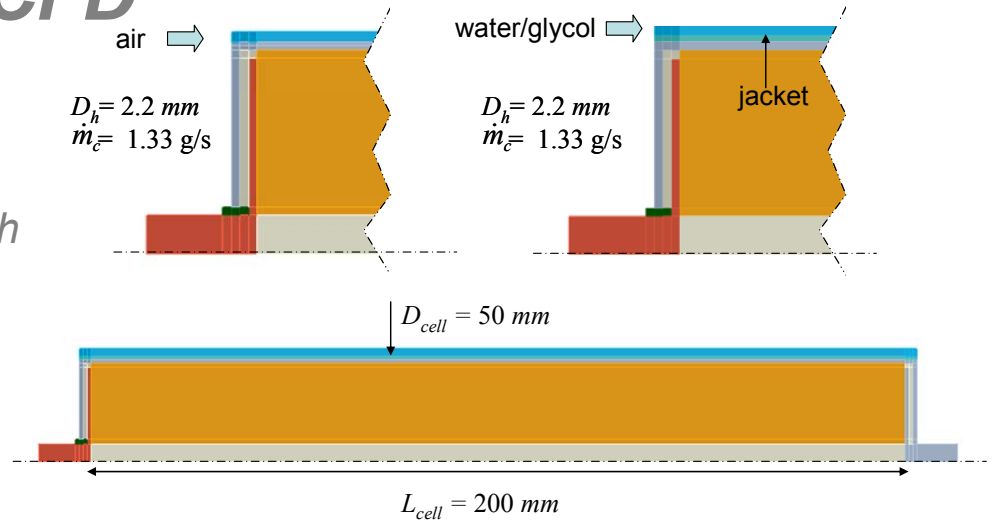
- CFD captures entrance effects.
- CFD model addresses battery internal heat flow and captures axially decreasing heat flux from cell to air.
- Internal heat flow through high conductivity material distributed inside a cell (such as container can) makes the axial gradient of cell surface temperature smaller than that of air temperature.

This result strongly implies that capturing the internal heat flow paths and thermal resistances inside a cell are important for the improved prediction of cell/battery thermal behaviors.

	ΔP [Pa] channel pressure loss	ΔT_1 [°C] coolant temperature change	ΔT_{max} [°C] maximum cell surface temperature to inlet air	ΔT_{cell} [°C] maximum cell internal temperature to inlet air	\bar{h} [W/m²K] mean heat transfer coefficient
Fully Developed Flow Relations with Constant Heat Flux	109.1	1.49	3.64	N/A	59.24
CFD	114.2	1.50	2.89	3.41	60.96

Air vs Water/Glycol CFD

Performance comparison analyses were made between **Air Cooling System** and **Water/Glycol Jacket Cooling System** in order to contrast the characteristics of each system.



- ✓ Heat Generation: 4 W per Cell
- ✓ Channel Inlet Air Temperature: 35°C
- ✓ Coolant Mass Flow Rate: 1.33 g/s
- ✓ Channel Gap Height: 1.1 mm
- ✓ 5 cm diameter, 20 cm height cell

Concluding Remarks

Air Cooling System

- The heat transfer coefficient (h) of an air cooling system is lower than that of liquid cooling systems.
- Due to the small heat capacity of air, it is difficult to accomplish temperature uniformity inside a cell or between the cells in a module.
- The temperature difference between coolant air and cell surface is sensitive to variations of channel height due to the small heat conductivity of air.
- Heat transfer coefficient is inversely proportional to D_h , while friction pressure loss in channel is inversely proportional to D_h^3 .
- Increasing heat transfer coefficient by reducing channel thickness is limited by the required blower power.
- The simplicity of an air cooling system is an advantage over a liquid coolant system.
- Air cooling could have less mass, has no potential for leaks, needs fewer components, and could cost less.

Concluding Remarks

Liquid Cooling System

- A water/glycol solution for a jacket cooling has much lower viscosity than dielectric mineral oil for direct cooling. Increasing the coolant flow rate in water/glycol system is not as severely restricted by the pump power as in a mineral oil system.
- Cell/module temperature uniformity can be effectively achieved in liquid cooling system due to the large heat capacity of liquid coolant.
- Water/glycol solutions generally have a higher thermal conductivity than oil. However, the effective heat transfer coefficient at the cell surface is greatly reduced due to the added jacket wall and air gap layer.
- Because of the added thermal resistances, h is not as sensitive to the variation of channel height in indirect liquid cooling systems.
- Liquid cooling systems are more effective in heat transfer and take up less volume.
- However, the added complexity and cost may outweigh the merits.
- Maintenance and repair of a liquid cooled pack is more involved and costlier. Indirect liquid cooling, with jackets, is easier to handle than direct liquid cooling.

Concluding Remarks

General

- Selection between air or liquid cooling depends on applications.
- Trade-off between performance, application, and cost must be considered
- It is recommended in liquid cooling system to use a small gap coolant channel to reduce system weight and volume by minimizing the amount of liquid coolant in a system operated at a given coolant flow rate.
- Capturing the internal heat flow paths and thermal resistances inside a cell using a sophisticated three-dimensional cell model is important for the improved prediction of cell/battery thermal behaviors.
- With the model we can look at turbulent flows, mixed conduction/convection, and phase change materials.