Battery Thermal Management System Design Modeling

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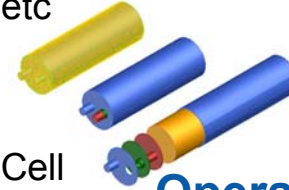
Motivations & Objectives

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
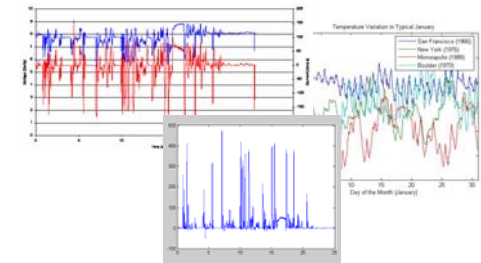
Cell Characteristics

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

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

Operating Conditions

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

Design Process

ANSYS   FLUENT   MATLAB
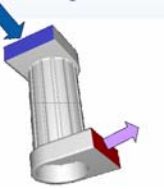
3D Component Analysis | System Analysis
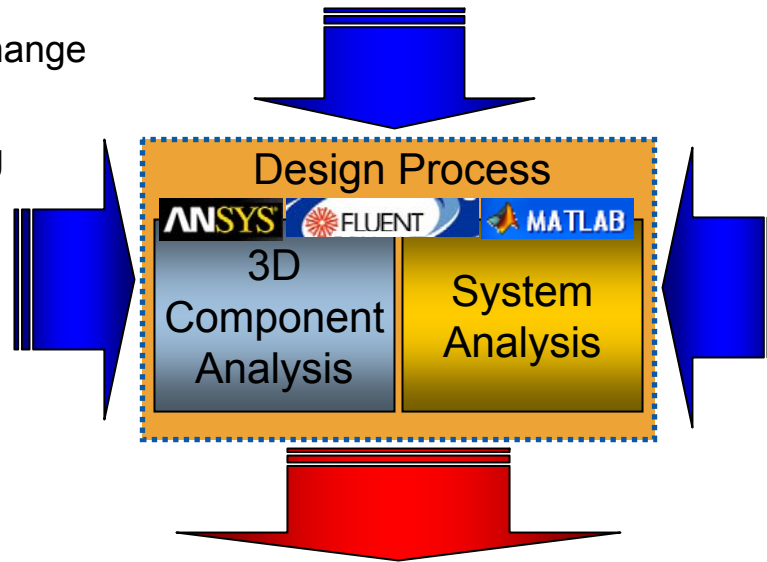
Battery Thermal Responses

• 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.

M=1.033 kg
Cp=961 J/kgK
h=30 W/m²K

Model

Experiment

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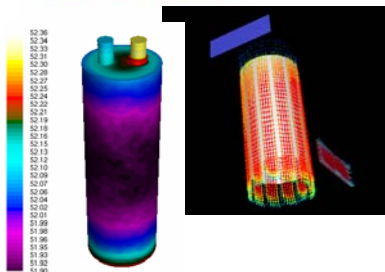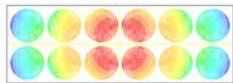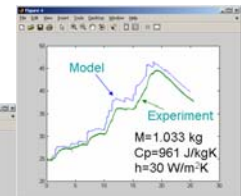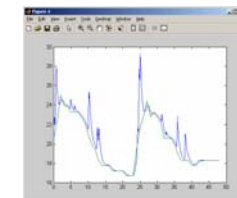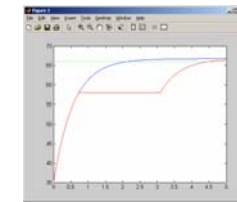
Approach

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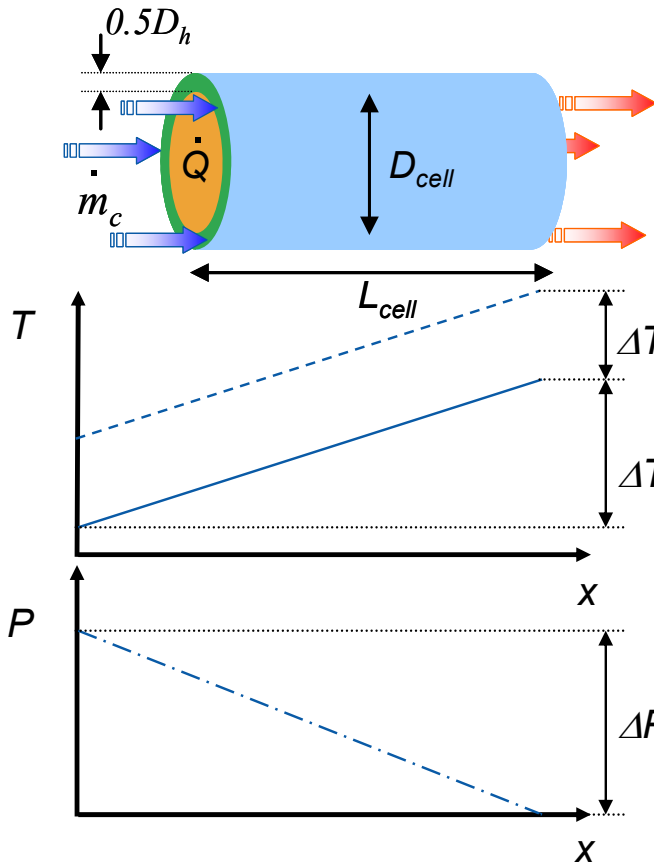
- - - - - cell surface temperature
———— coolant mean temperature
— · — · — pressure

Fully Developed Laminar Flow Analysis Annular Channel Cooling

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

$$c_f \, \mathrm{Re} = 24$$

$$\mathrm{Nu} = 5.385$$

where, $\quad \mathrm{Re} = \dfrac{V D_h}{\nu}$, $\quad \mathrm{Nu} = \dfrac{h D_h}{k}$

hydraulic diameter
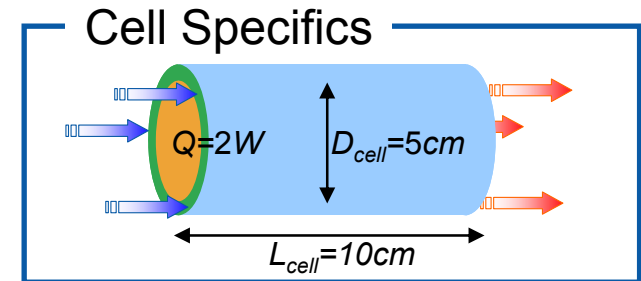
$D_h = 4\, A_c\, / p$
where
A_c : *area section of the channel*
p :*perimeter of the channel*

mean velocity

$V = \dot{m} / (\rho A_c)$
where
ρ : *coolant density*
$\dot{m}$: *coolant mass flow rate*

Cell Specifics

$Q=2W$ $D_{cell}=5cm$

$L_{cell}=10cm$

Heat Transfer Fluid Specifics

	Air	Mineral Oil	Water/Glycol
ρ :g/m3)	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 (m2/s)	1.4607e-5	5.6e-5	2.582e-6

System Responses

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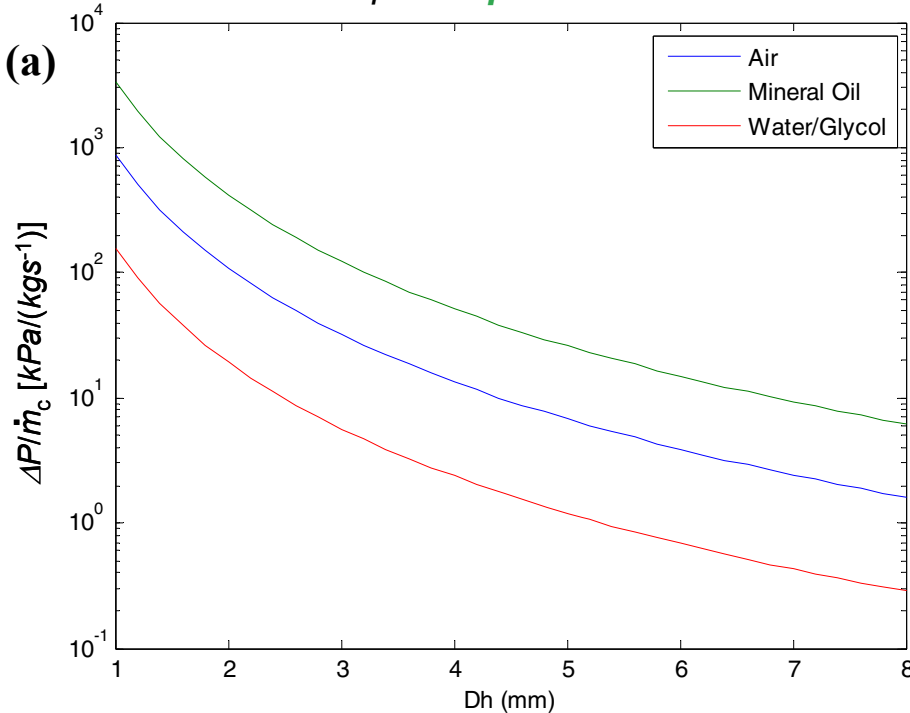
Control Parameters

$\dot{m}$: Coolant Mass Flow Rate

D_h : Hydraulic Diameter of Coolant Channel
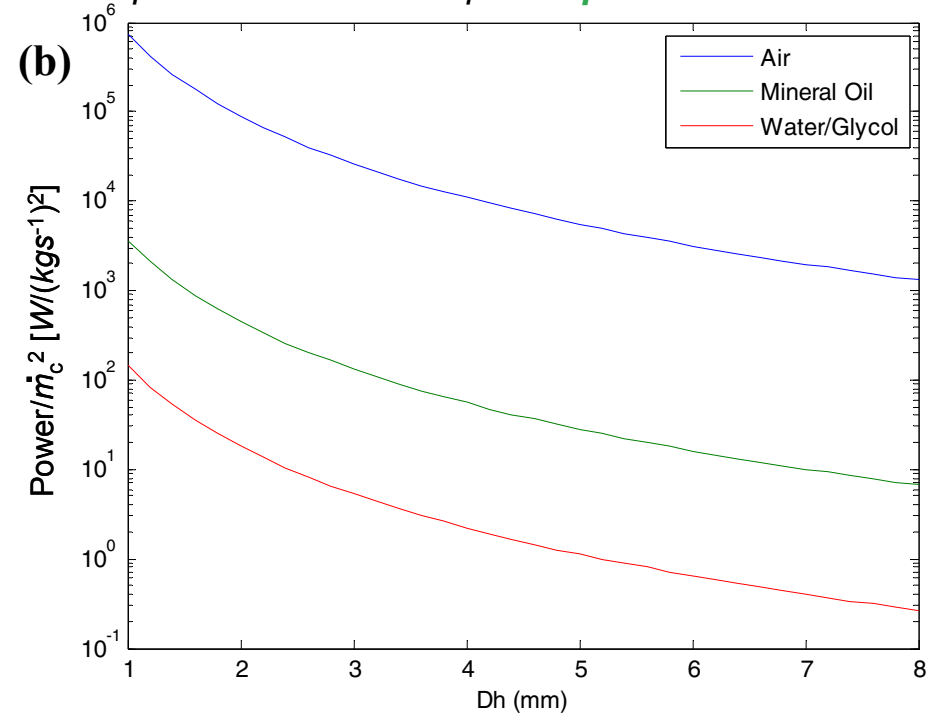
Channel Pressure Loss ΔP

$$\Delta P \sim \frac{\dot{m}_c v}{D_h^3} \qquad \frac{\partial \Delta P}{\partial D_h} \sim -\frac{\dot{m}_c v}{D_h^4}$$

*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
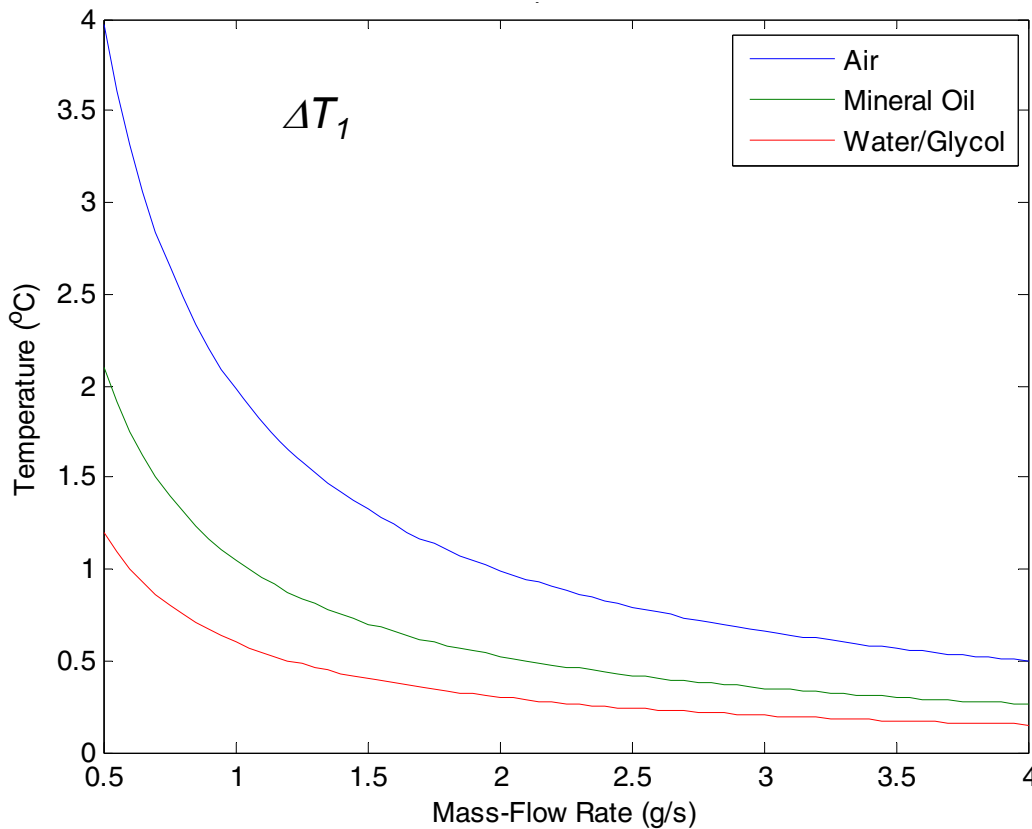
- To achieve the temperature uniformity over a cell, it is preferred to keep coolant temperature change in the channel as small as possible.

- 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).

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

Temperature Difference between Coolant Bulk and Cell Surface ΔT_2

Temperature Difference Between Coolant & Cell Surface

ΔT_2

- Air
- Mineral Oil
- Water/Glycol

Temperature ($^\circ$C) vs D_h (mm)

Heat Transfer Coefficient

h

- Air
- Mineral Oil
- Water/Glycol

h *at direct contact surface for water/glycol system*

h (W/m^{2}K) vs D_h (mm)
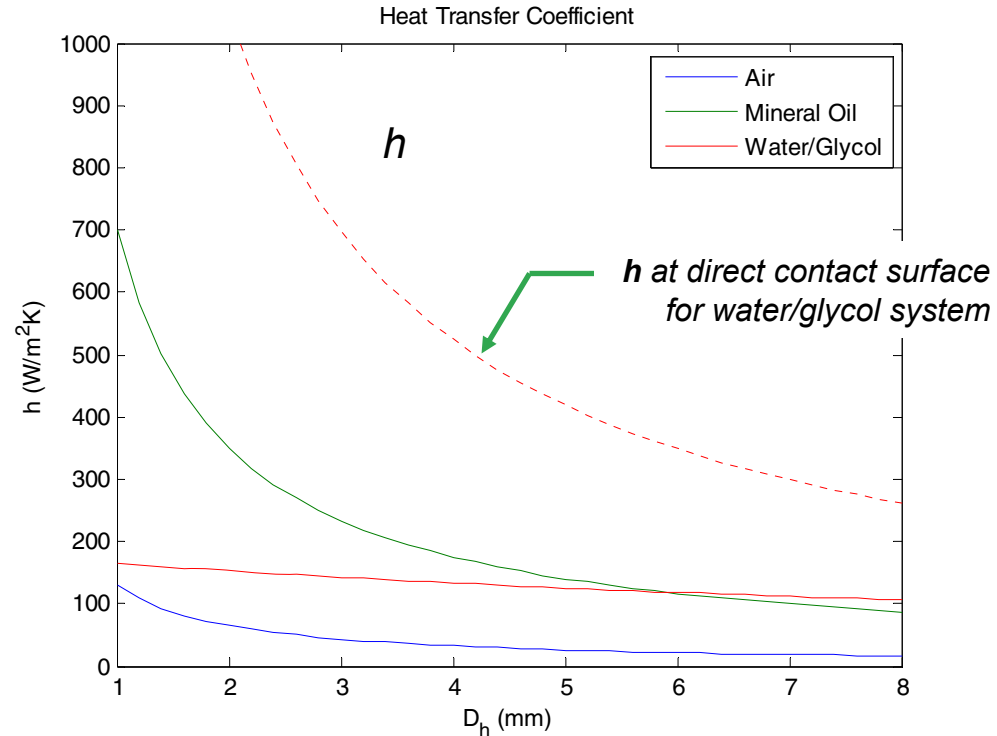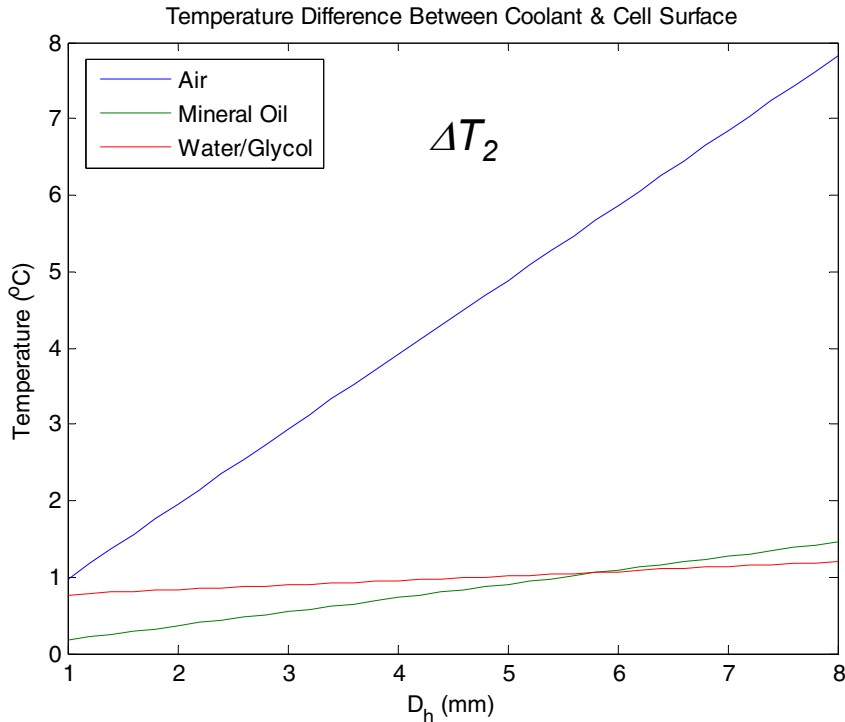
- ΔT_2 varies linearly with D_h with slope being proportional to $1/k$.
- ΔT_2 rapidly increases with D_h in air cooling due to its small thermal conductivity.
- The heat transfer coefficient (h) evaluated at cell surface for water/glycol jacket cooling is greatly reduced and not sensitive to channel 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 $\quad \Delta T_{max}\,(= \Delta T_1 + \Delta T_2)$
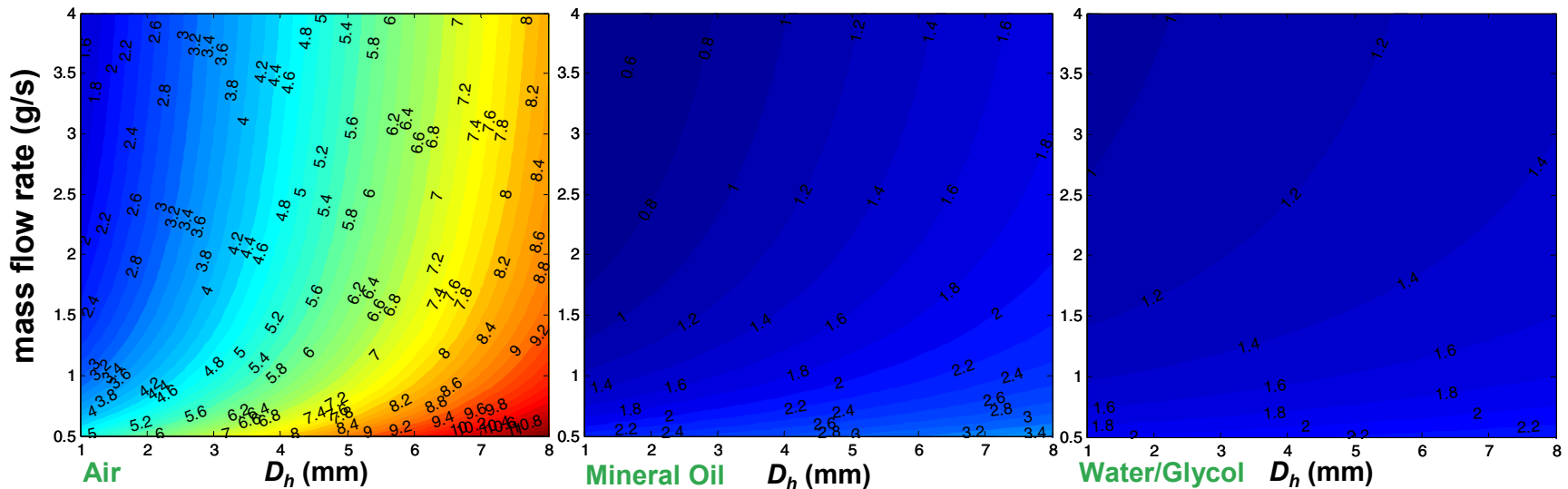
- ΔT_{max} in the air system are much higher compared with other fluid systems due to its small heat capacity and thermal conductivity.
- The air system: ΔT_{max} is dominated by and sensitive to D_h.
- The water/glycol jacket cooling system: ΔT_{max} is not very sensitive to D_h, and ΔT_{max} is not a strict limiting thermal design factor in a water/glycol system.

Optimizing Operation Parameters

- Air Cooling System

Cell Specifics

$Q=2W$ $D_{cell}=5cm$ $L_{cell}=10cm$
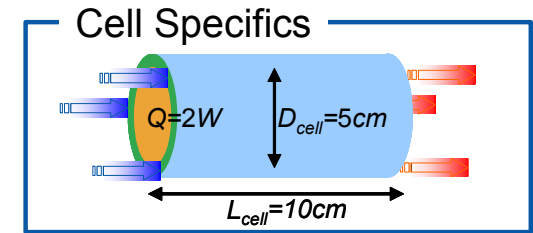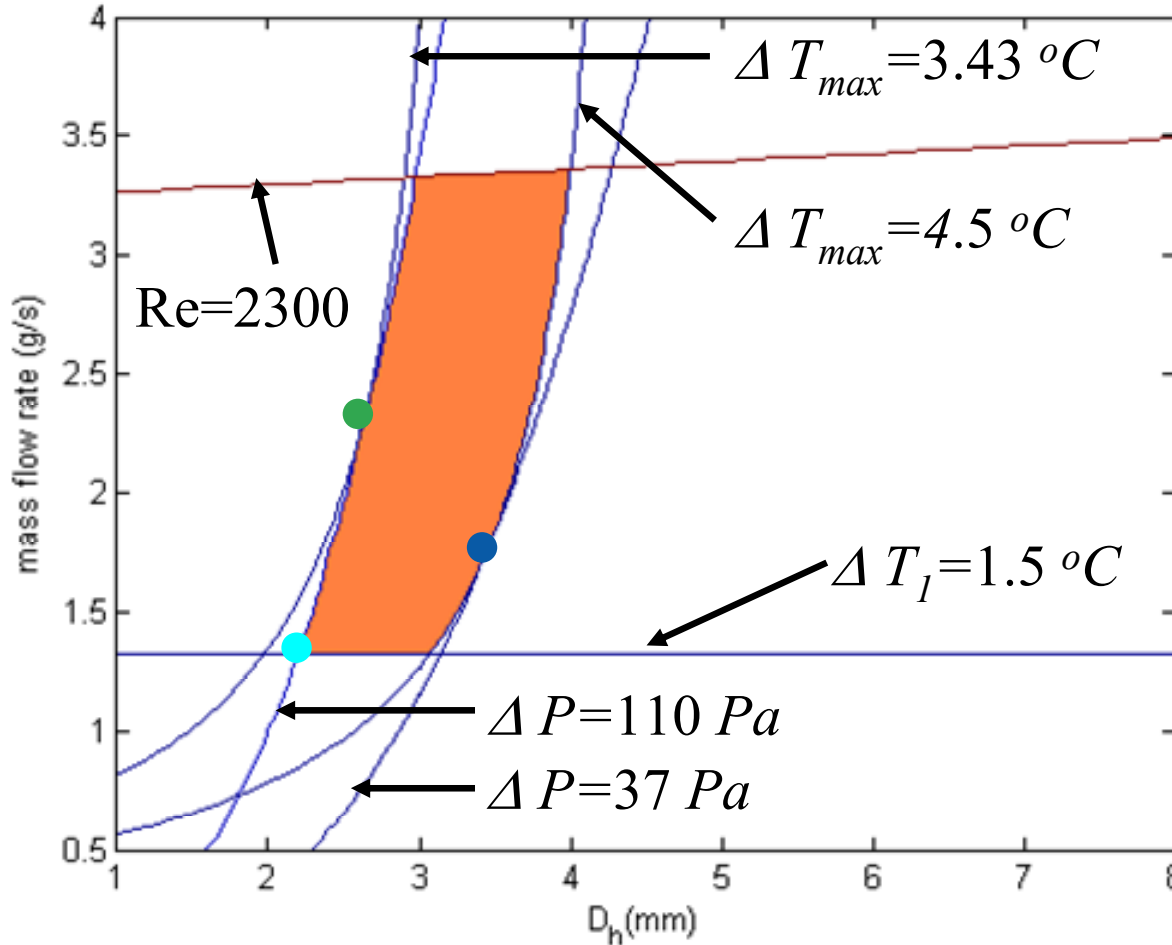
Confining Factors

Colored Zone satisfies
Re < 2300
$\Delta P < 110\ Pa$
$\Delta T_1 + \Delta T_2 < 4.5\ ^oC$
$\Delta T_1 < 1.5\ ^oC$

$\Delta T_{max}=3.43\ ^oC$

$\Delta T_{max}=4.5\ ^oC$

Re=2300

$\Delta T_1=1.5\ ^oC$

$\Delta P=110\ Pa$

$\Delta P=37\ Pa$

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

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Trend Validation: Module Liquid Cooling Experiment
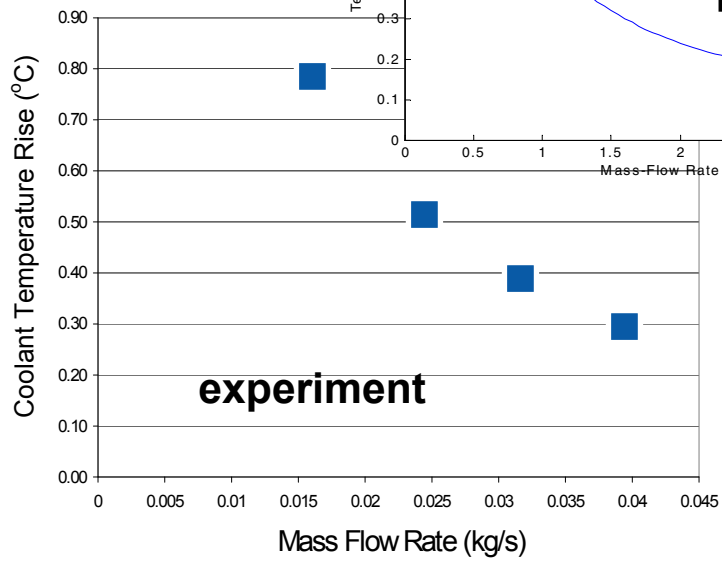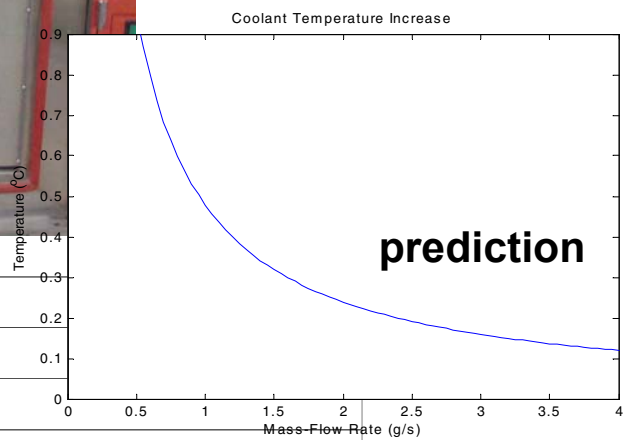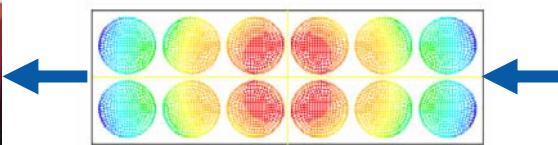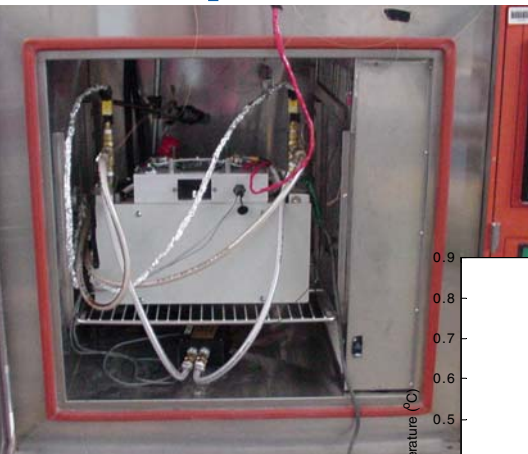
Tested Module Cooling System

- 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.

Coolant Temperature Increase

prediction

experiment

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

Coolant Channel

Can

Cell Core

Terminal   Current Collector   Terminal

Temperature Distribution

NOTE: Radial direction length is exaggerated.

38.41
38.24
38.07
37.90
37.73
37.56
37.39
37.22
37.05
36.88
36.71
36.53
36.36
36.19
36.02
35.85
35.68
35.51
35.34
35.17
35.00
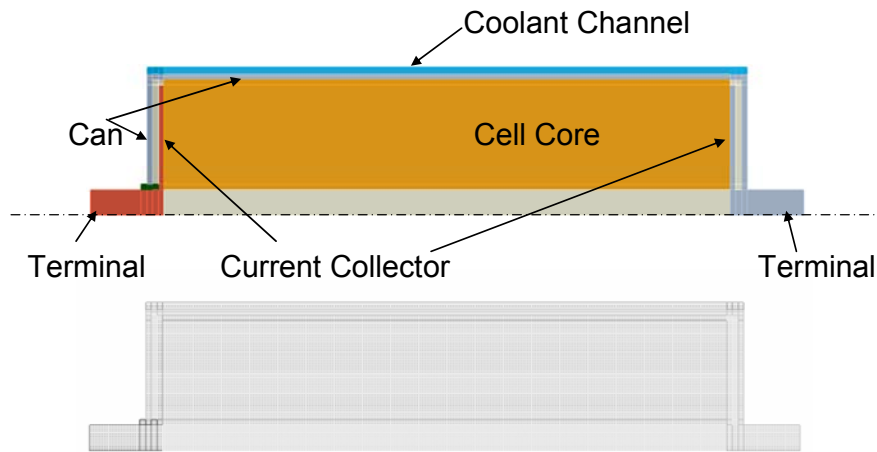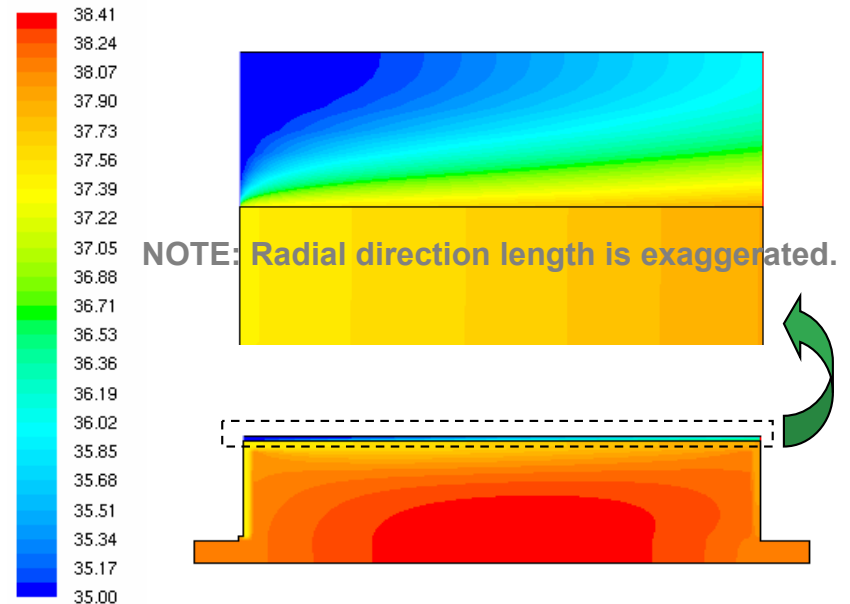
CFD Predictions:
Temperatures, h and Surface Heat Flux Profiles
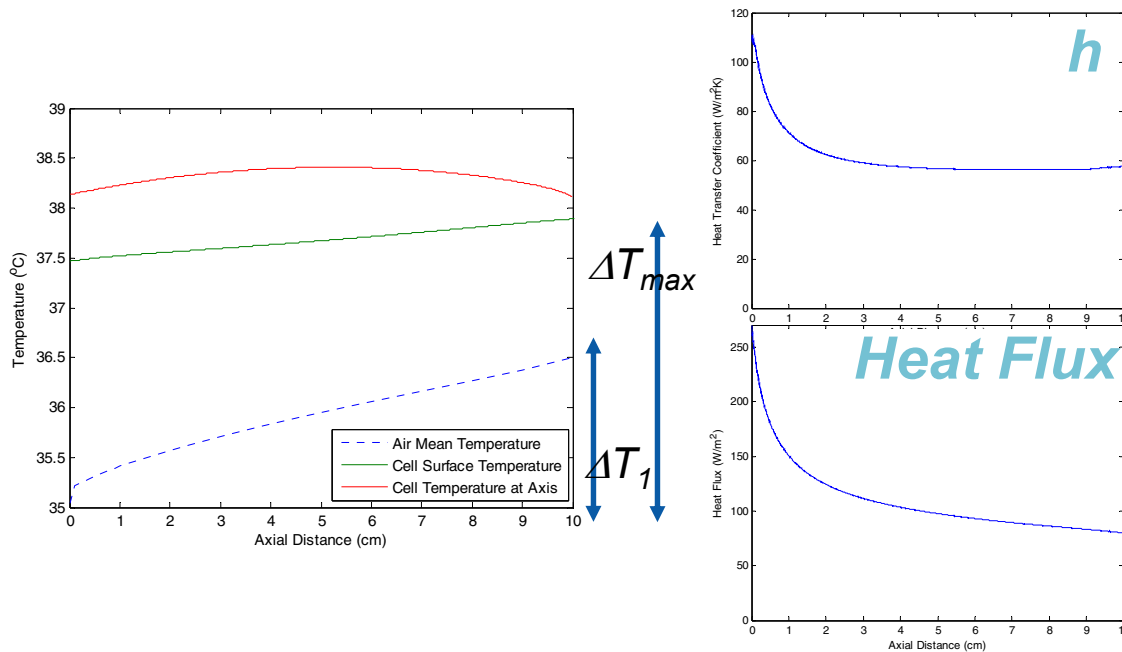
ΔT_{max} **Disagreement**

- 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.*

air ⟹   water/glycol ⟹

jacket

$D_h = 2.2$ *mm* $D_h = 2.2$ *mm*
$\dot{m}_c = 1.33$ g/s $\dot{m}_c = 1.33$ g/s

$D_{cell} = 50$ *mm*

$L_{cell} = 200$ *mm*

air   water/glycol

jacket

aluminum can   aluminum can

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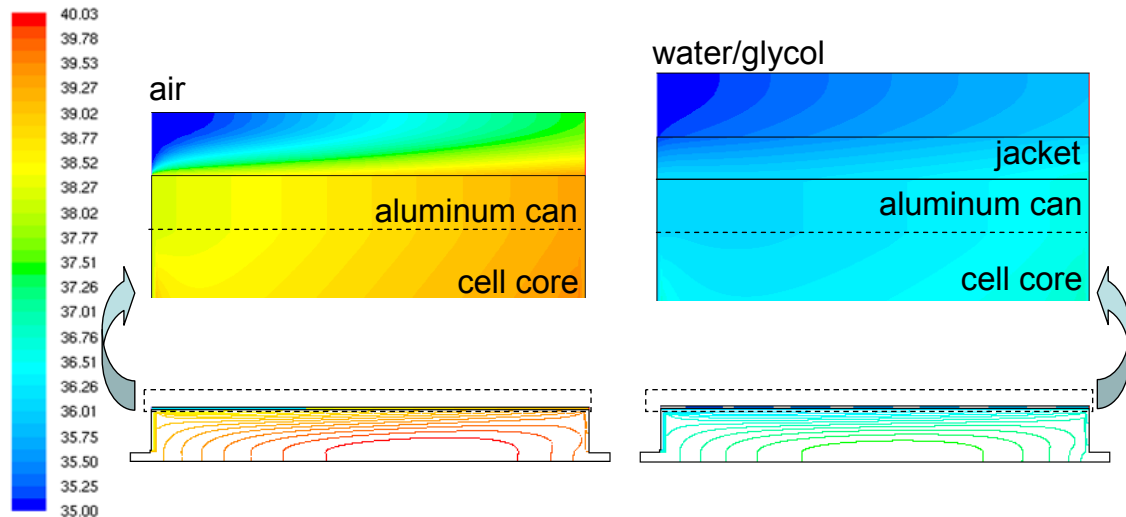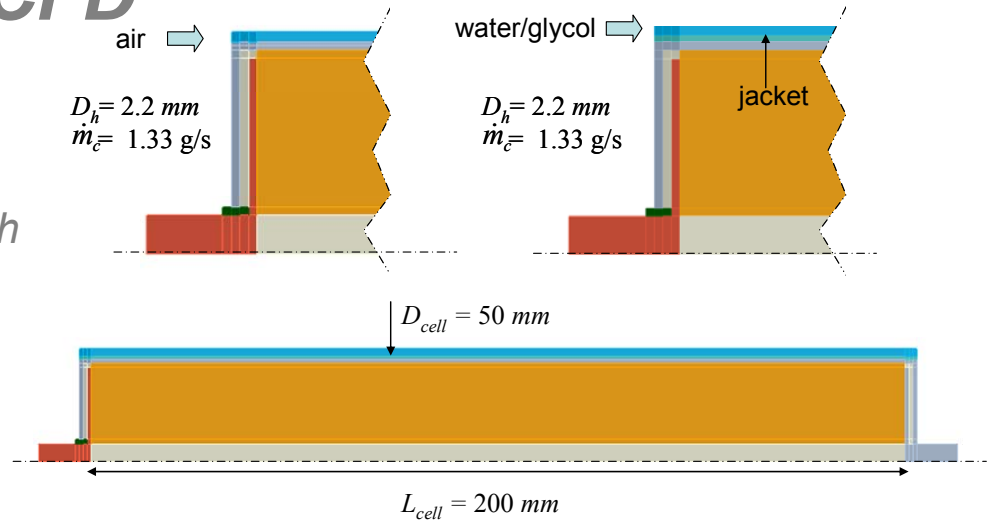
✓ Heat Generation: 4 W per Cell
✓ Channel Inlet Air Temperature: 35°C
✓ Coolant Mass Flow Rate: 1.33 g/s
✓ Channel Gap Height: 1.1 mm
✓ 5 cm diameter, 20 cm height cell

40.03
39.78
39.53
39.27
39.02
38.77
38.52
38.27
38.02
37.77
37.51
37.26
37.01
36.76
36.51
36.26
36.01
35.75
35.50
35.25
35.00

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.