Thermal Control of Power Electronics of Electric Vehicles with Small Channel Coolant Boiling

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Sponsored by L. Slezak and D. Anderson (Vehicle Systems)

Project ID: VSS132

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Overview

Timeline

- Project start date – FY14
- Project end date – FY15
- Percent complete – 75%

Barriers

- Weight – eliminate the second radiator for hybrid electric vehicles (HEVs)
- Performance and lifetime of electronic components – temperature
- Efficiency – junction temperature control
- Applications – cooling of high power electronic modules for HEVs & electric vehicles (EVs)

Budget

- Total project funding (to date): $355K
- Funding received prior to FY15: $150K
- Funding for FY15: $205K

Partners

- Interactions/collaborations
  - Advanced Power Electronics & Electrical Machines (APEEM)
  - Oak Ridge National Laboratory (ORNL)
  - Dana Corporation
  - Bergstrom
  - Eaton Corporation
- Project lead
  - Argonne National Laboratory

Relevance

- Elimination of a low temperature cooling system
- Power electronic modules can operate at high powers or conversely have smaller footprints
- Reduction in size & weight of power electronics package => reduced costs
  - ✓ current costs ~$30/kWh, target is $8/kWh by 2020
- Secondary benefits of the technology
  - ✓ improved efficiency and reliability of power electronics at higher operating conditions
    - ➢ smaller inverters delivering same level of power to motor
  - ✓ increased lifetimes of the power electronic components ($$ savings)

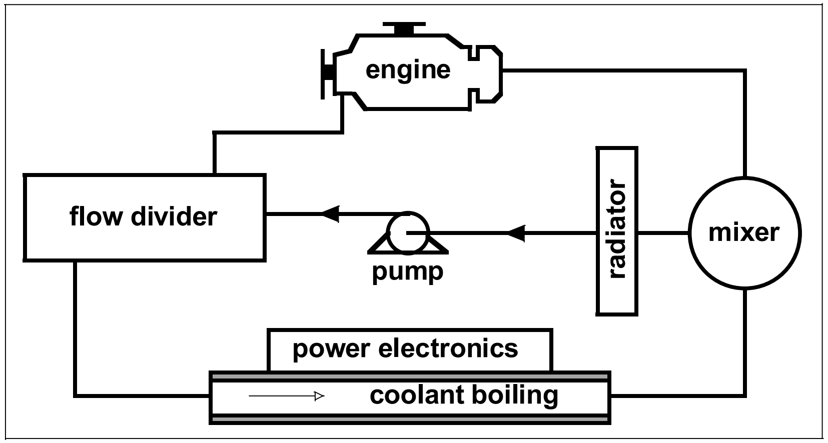
Toyota Prius (2004) inverter and voltage converter unit

BOSCH

Delphi inverter

Objectives

Use subcooled boiling in the cooling channel to enhance the cooling of vehicle power electronics for hybrid and all-electric vehicles



Objectives:

- Explore the potential of subcooled boiling for vehicle power electronics cooling
- Conduct numerical heat transfer simulations
- Experimentally investigate subcooled boiling heat transfer

Targets Addressed:

- Eliminating the low-temperature cooling system for HEVs -- reduce the cost and weight
  - ✓ Reduced pumping power and parasitic losses
- Using subcooled boiling to increase heat removal capacity
- Controlling junction temperature -- improve the efficiency and lifetime of electronic components
- Applying to high power density electronics
  - ✓ Wideband gap semiconductors based power electronics -- heat flux: 200-250 W/cm^2
- Simple cooling system configuration
  - ✓ Integrated into the main engine cooling system

Approach/Strategy

- Heat transfer simulations
  - ✓ Analyze benefits of subcooled boiling over currently used convective heat transfer
  - ✓ Investigate various parameter effects on subcooled boiling
    - ➢ Thermal conductivity of thermal interface material (TIM)
    - ➢ Flow velocity
    - ➢ Inlet flow temperature
    - ➢ Heat flux
- Experimental measurements
  - ✓ Modify the heat transfer test facility to connect with the cooling module of power electronics
  - ✓ Measure subcooled flow boiling heat transfer coefficients under vehicle power electronics cooling conditions and compare with simulation results
  - ✓ Develop predictive models for the subcooled boiling heat transfer coefficient for power electronics geometry cooling systems

Demonstrate the applicability of subcooled nucleated boiling cooling technology for power electronics for HEVs and EVs

Approach - Milestones

Month/ Year	Milestone or Go/No-Go Decision	Description	Status
Sep./ 2014	Milestone	Numerical heat transfer simulations (COMSOL) to establish the advantages of subcooled nucleated boiling for power electronics cooling	Completed
Dec./ 2014	Milestone	Numerical simulations on selected power electronics cold plate	Completed
Mar./ 2015	Milestone	Design & modify the current subcooled boiling test loop to integrate a power electronic module (inverter) heat sink for tests	Completed
July/ 2015	Milestone	Measure subcooled boiling heat transfer coefficients for a typical power electronic module cooling channel and compare the data with the simulations	On going
Sep./ 2015	Milestone	Develop predictive models for the subcooled boiling heat transfer coefficient based on the experimental data for power electronics geometry cooling systems	Will be done

Key Conditions of Subcooled Boiling Simulations

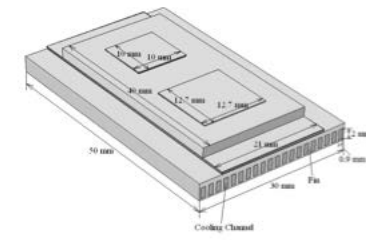
- Use of conventional engine coolant -- 50/50 ethylene glycol/water (EG/W) mixture
- Coolant fluid inlet temperature of 105 C -- using engine cooling pumping system
- Coolant under 2 atmosphere pressure -- same as engine cooling system pressure
- Flow velocity around 0.16 m/s (laminar flow)
  - ✓ Lower pressure drops and pumping power requirements
- Coolant fluid outlet temperature below the saturation point -- no vapor in rest of the system
- Cooling channel wall temperature of 10-30° C above the saturation point (~129° C under 2 atm)

Subcooled boiling

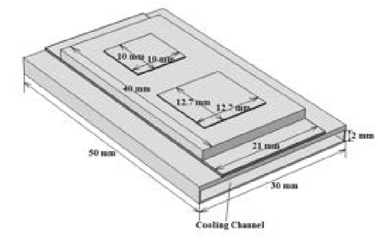
Previous Accomplishments -- FY14

Effects of Various Parameters on Subcooled Boiling

- Modeling Geometry (Toyota Lexus):



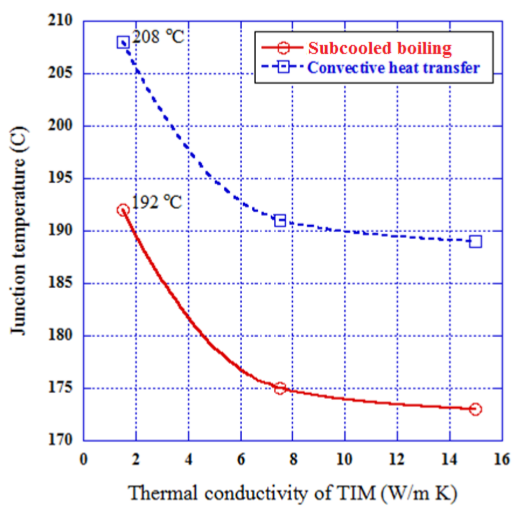
(a) With fins



(b) Without fins

1. TIM Thermal Conductivity Effects

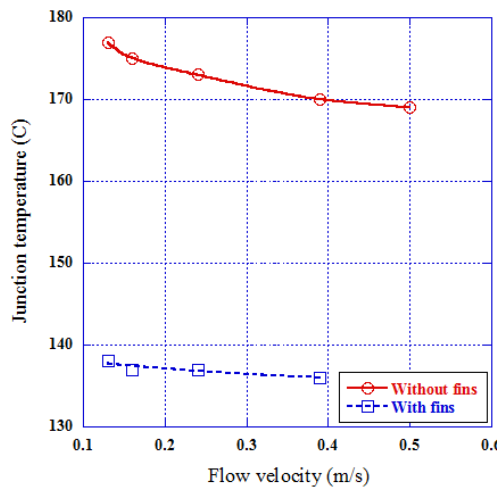
- Double-sided cooling without fin for a 100-W/cm^2 heat flux



- Subcooled boiling with a 7.5 W/m·K TIM can control the junction temperature under 175 C
- Fins can be eliminated in double-sided subcooled boiling cooling

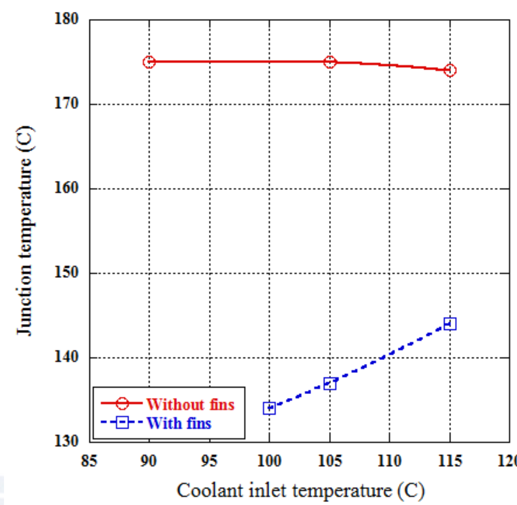
2. Coolant Flow Velocity Effects on Subcooled Boiling

- Double-sided cooling with a 7.5-W/m·K TIM for a 100-W/cm^2 heat flux



- Coolant flow velocity range: 0.05 m/s - 0.4 m/s (100 W/cm^2 heat flux with fins)

3. Coolant Inlet Temperature Effects on Subcooled Boiling



Previous Accomplishments -- FY14

Comparison of Convective and Subcooled Boiling Heat Transfer Simulations for Toyota Lexus Power Electronics Package

- TIM - 7.5 W/m·K

	Subcooled boiling cooling system				Laminar flow cooling system *	
Coolant inlet temperature (°C)	105	105	105	105	70	70
Total heat flux on IGBT and Diode surfaces (W/cm^2)	100	125	100	250	127	100
Coolant flow velocity (m/s)	0.16	0.16	0.16	0.16	0.24	0.24
Fins in the channel	No	Yes	Yes	Yes	Yes	Yes
Cooling system	Double-side	Single-side	Single-side	Double-side	Double-side	Single-side
Junction temperature (°C)	175	175	160	175	150	175

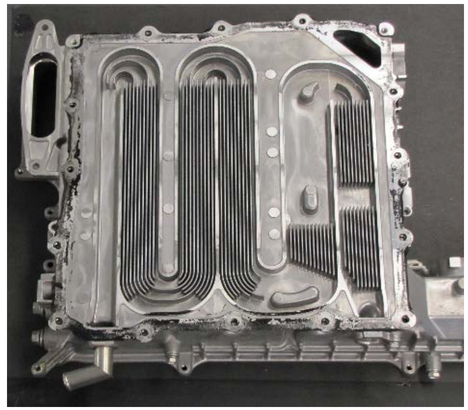
* Literature base case: Bennion, K. et al., 2009 simulation results

- Without fins, double-sided subcooled boiling can cool current systems
- With fins, subcooled boiling can increase the cooling rate by 25% or reduce the junction temperature
- With fins, double-sided subcooled boiling can cool wideband gap semiconductors up to 250 W/cm^2

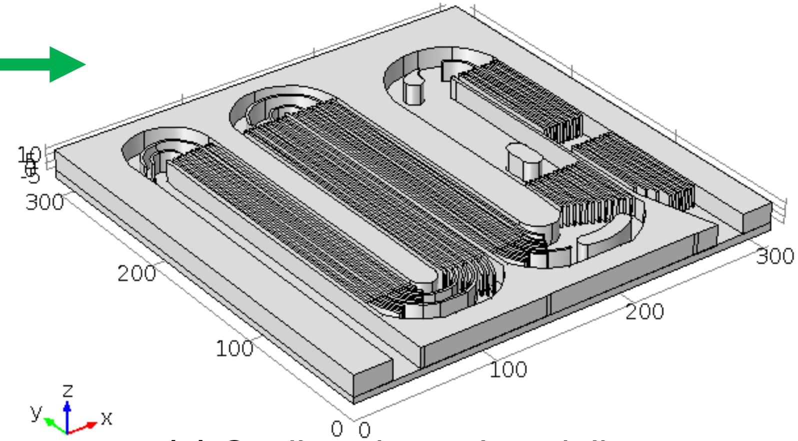
Technical Accomplishments -- FY15

Toyota Prius Power Electronics Package (Modeling Geometry COMSOL)

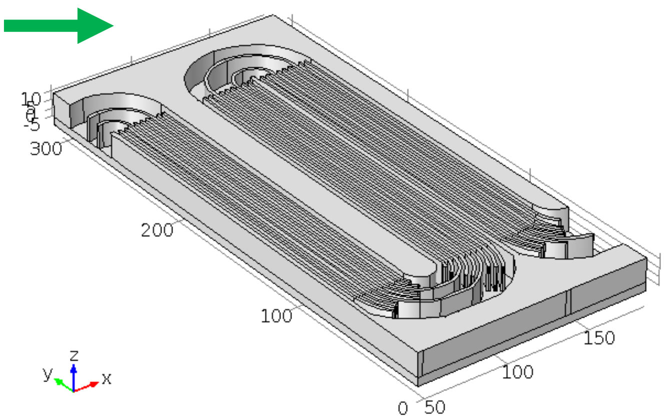
(a) Cold plate



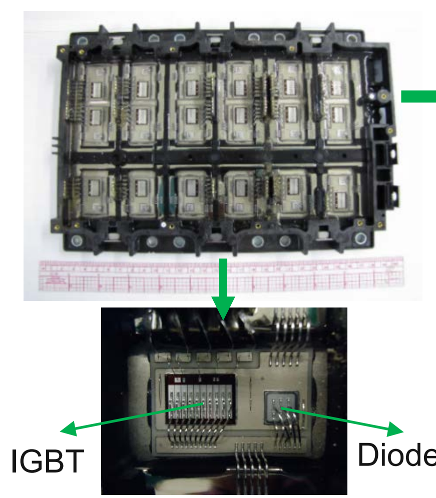
(b) Cooling channels



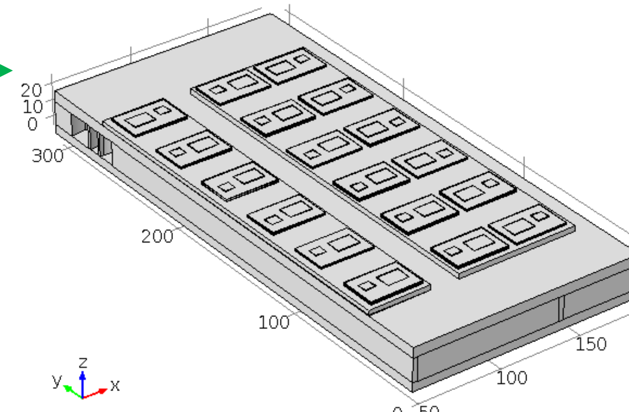
(c) Cooling channel modeling geometry (unit in mm)



(d) Cooling channels used for power electronics cooling



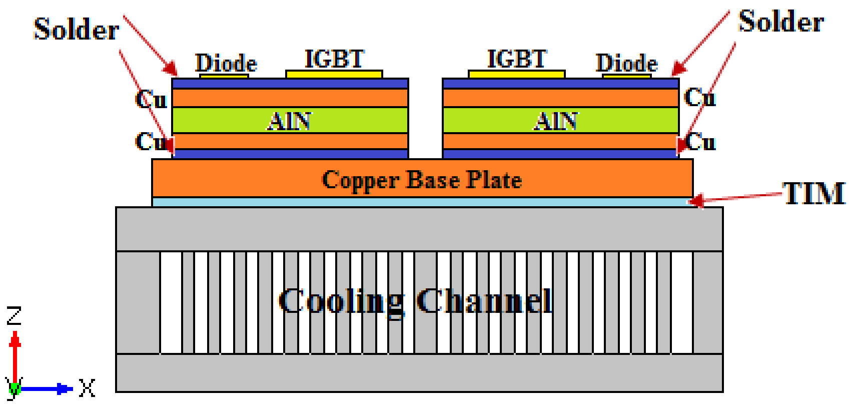
(e) Power electronics module



(f) Final modeling geometry for power electronics module

Technical Accomplishments -- FY15

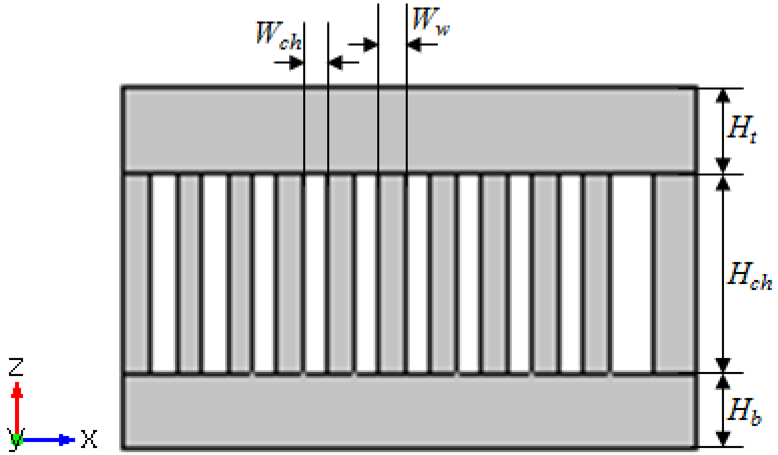
Materials and Dimensions of Each Component



Side view of power electronics and cooling channels (not to scale)

Materials	*x* (mm)	*y* (mm)	*z* (mm)
Silicon IGBT	13.0	9.0	0.51
Silicon diode	6.5	6.0	0.32
Copper layer	32	21.5	0.41
AIN layer	32	21.5	0.64
Copper base plate	73	225	3.0
Solder layer	32	21.5	0.1
TIM: Thermal grease	73	225	0.1

Aluminum cooling channel (10 channels per set):



Parameter	Value (mm)
H_{ch}	14
H_b	5
H_t	6
W_{ch}	1.75
W_w	1.75

Technical Accomplishments -- FY15

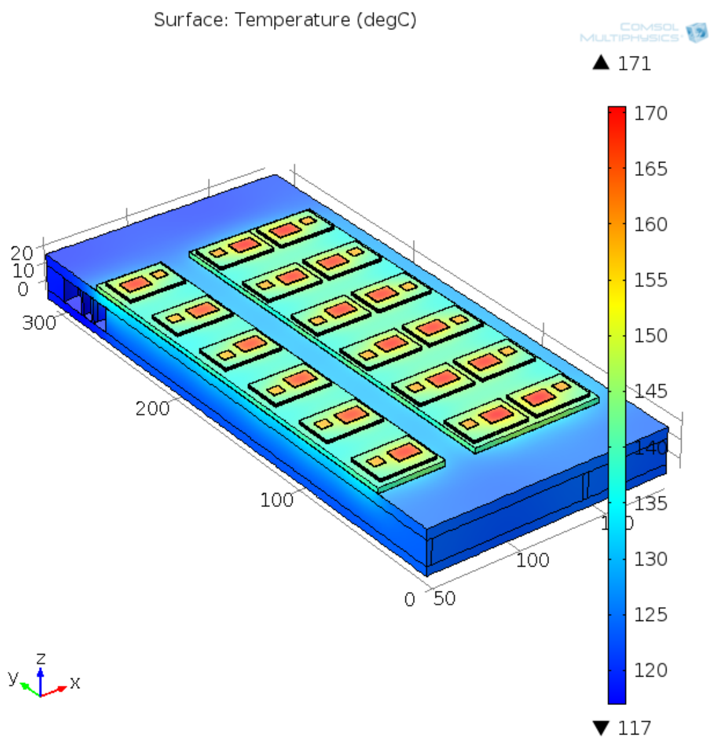
Toyota Prius Heat Sink Simulation Results

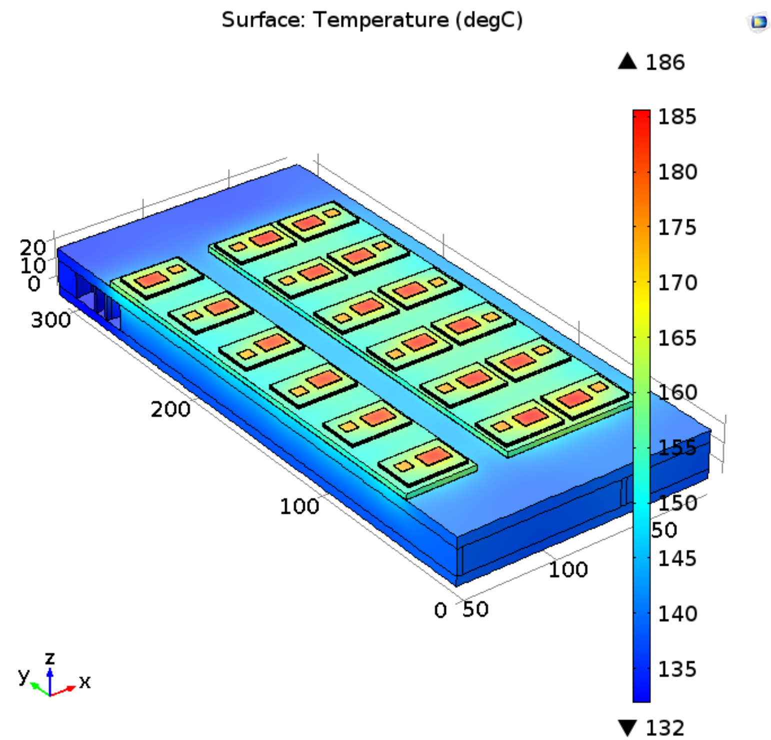
Current technology -- Single phase laminar flow:

- Heat flux: 100 W/cm^2
- Coolant inlet temperature: **70 C**
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: **< 175 C**

Single phase laminar flow:

- Heat flux: 100 W/cm^2
- Coolant inlet temperature: **105 C**
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: **186 C**

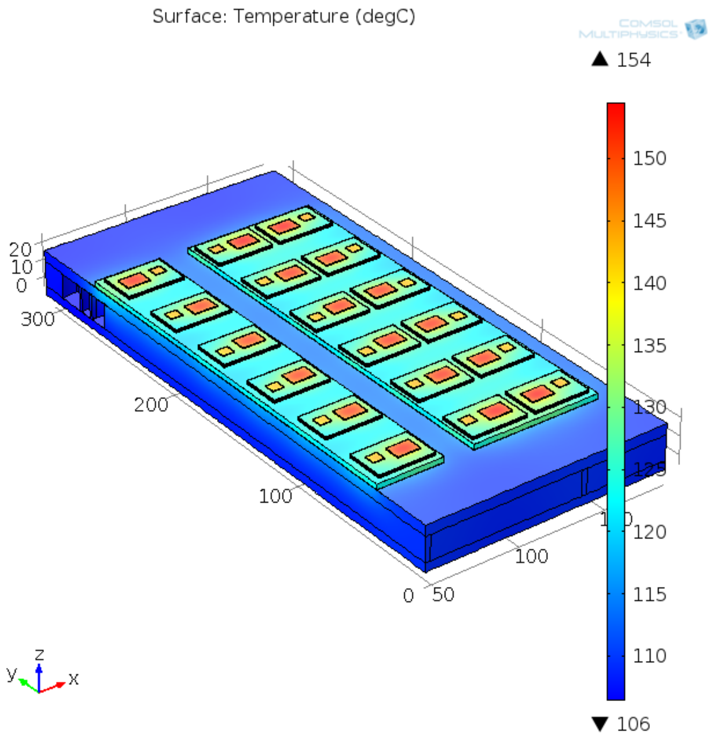




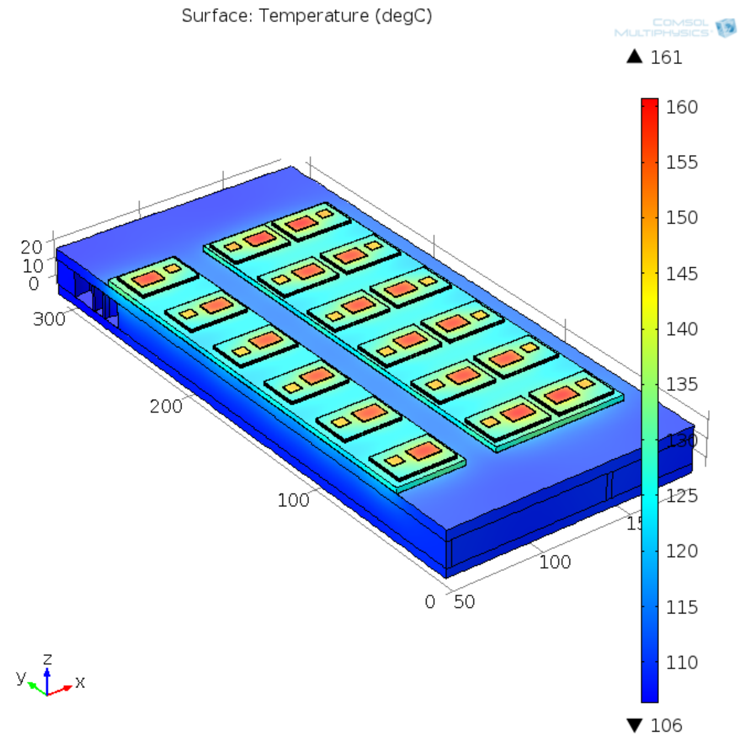
Single phase convective heat transfer will not work at coolant temperatures of 105 °C

Technical Accomplishments -- FY15
Toyota Prius Heat Sink Simulation Results

Subcooled boiling cooling system:
- Heat flux: *100 W/cm²*
- Coolant inlet temperature: **105 C**
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: **154 C**



Subcooled boiling cooling system:
- Heat flux: *114 W/cm²*
- Coolant inlet temperature: **105 C**
- Coolant flow velocity: 0.16 m/s
- TIM: 1.5 W/m K
- Junction temperature: **161 C**



- With subcooled boiling, the coolant inlet temperature can be increased to 105 ° C
- With subcooled boiling, the heat flux for Prius power electronics can be increased to 114 W/cm^2 compared to the single phase convective cooling

Technical Accomplishments -- FY15

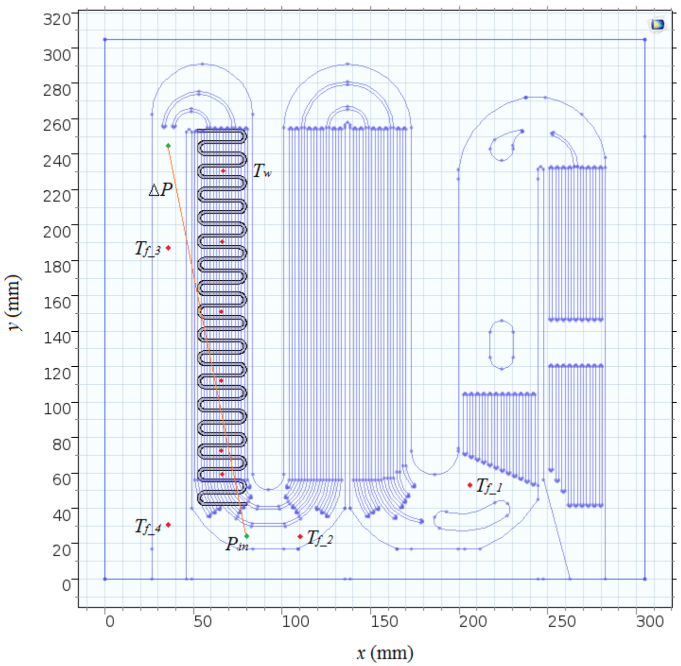
Simulation Results

Subcooled boiling technology for Toyota Prius power electronics cooling provides:

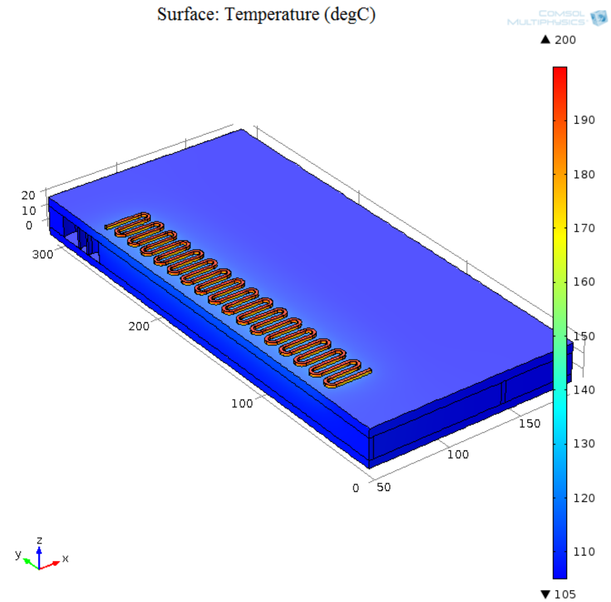
- Increased coolant inlet temperature of 105 C
  - ✓ Elimination of the second low temperature cooling system
- Control of Junction temperature <175 C
- Low flow velocity
  - ✓ Low pressure drop and pumping power requirement
- Increased cooling rate by **14%** compared to the current technology based on convective heat transfer
  - ✓ The heat flux is limited by the temperature rise of the coolant
    - ➢ Constraint to keep coolant outlet temperature below the saturation point
  - ✓ The heat flux can go higher if the cooling channel is altered from series to parallel channels

Technical Accomplishments -- FY15

Experimental Design



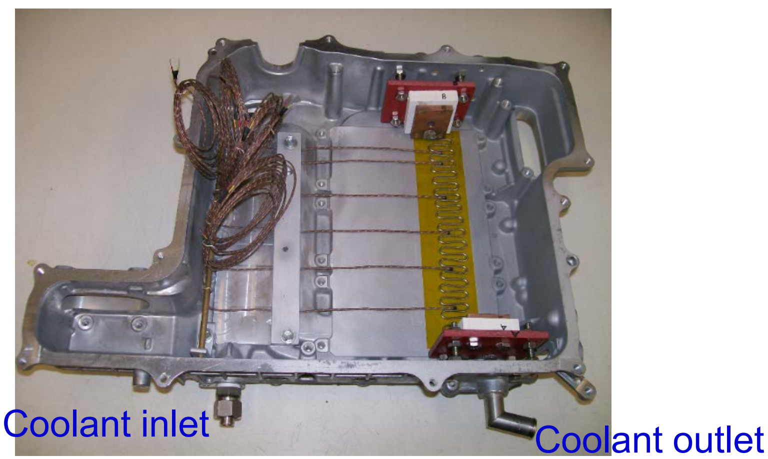
(a) Heating wire, TCs and pressure transducers set-up on the heat sink



(b) Heat input from heating wire equivalent to 100 W/cm^2 heat flux on IGBT and diode pairs

Heating wire to supply heat fluxes (simulating IGBT and diode on the cold plate):

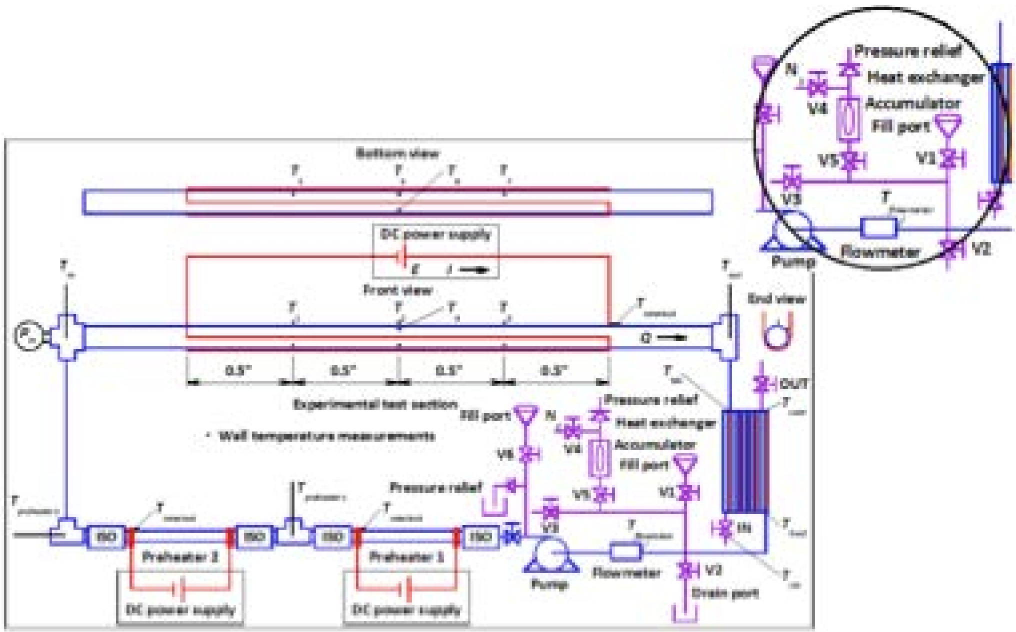
- Nichrome 80
- Diameter: 0.072"
- Electrical resistance: 0.1254 Ohms/ft nominal
- Wire spacing: 3/16"
- Total heating wire length: ~40"

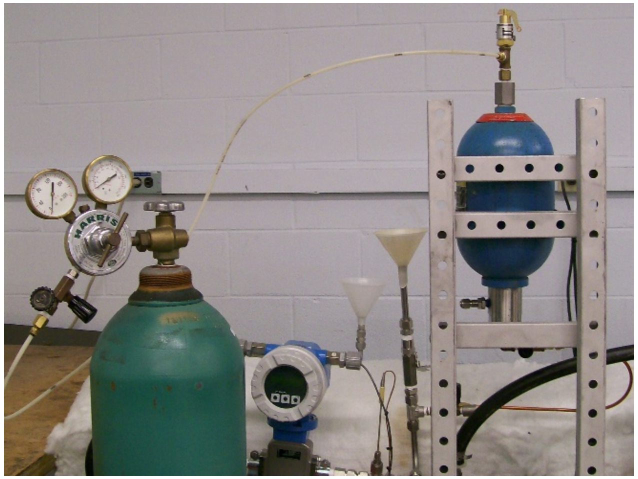


(c) Heating wire attached on the cold plate

Technical Accomplishments -- FY15

Modified Experimental Subcooled Boiling Test Loop

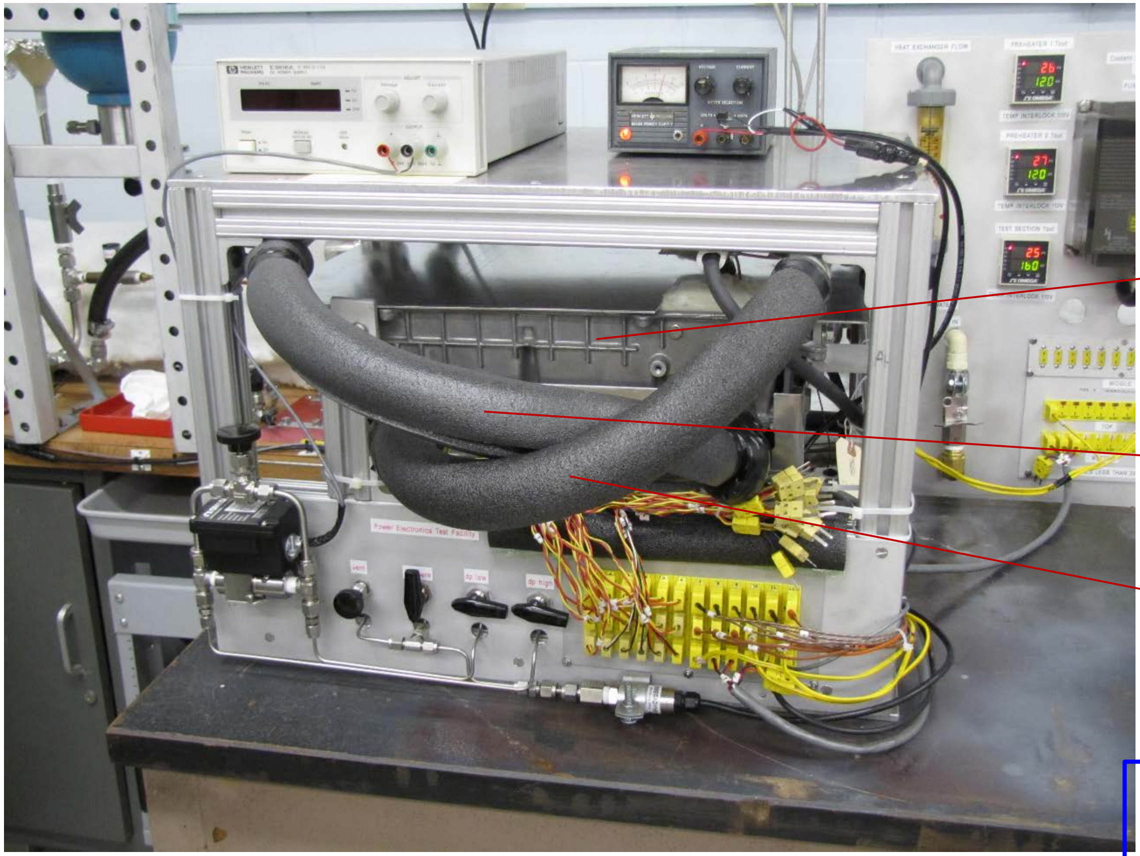




Pressurized system

Technical Accomplishments -- FY15

Heat Sink Test Section Assembled and Incorporated on the Test Loop



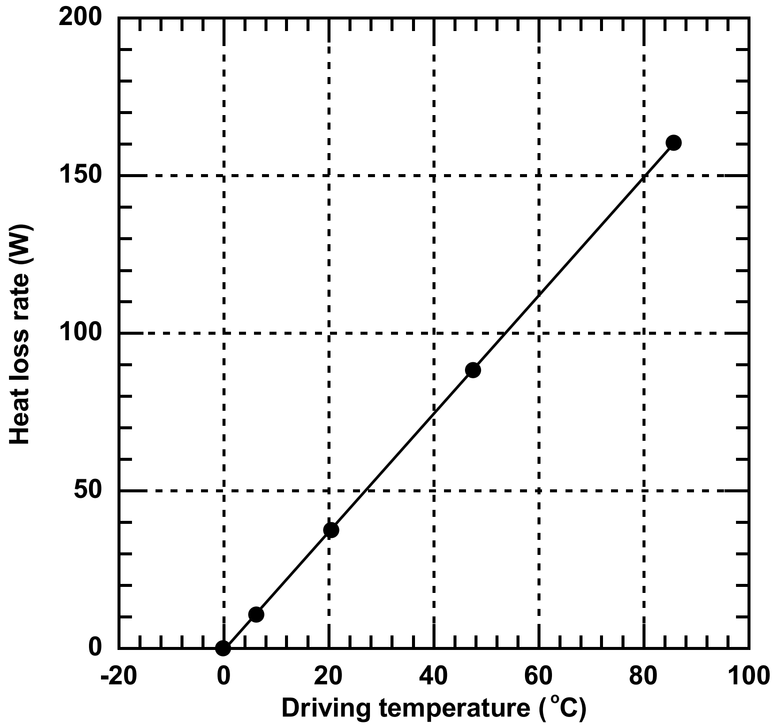
Heat sink integrated on to the test section loop

- Experiment test conditions:
  - ✓ Coolant: 50/50 EG/W mixture
  - ✓ Coolant inlet temp: 70-125 C
  - ✓ Flow velocity: 0.05-1.0 m/s
  - ✓ Max power input: up to 1500 W
  - ✓ Pressure: ~2 atm

Technical Accomplishments -- FY15

Heat Loss Calibration

- No flow heat loss tests
  - ✓ Applied five power inputs to bring its wall temperature to selected levels
    - ➢ Corresponding heat loss = applied power
- Heat loss characteristics
  - ✓ Heat loss due to the high thermal conductivity of aluminum
    - ✓ Predicted well with the fitting equation
    - ➢ Linearly depended on the driving temperature
    - ✓ Incorporated into the data reduction procedures
      - ➢ For single-phase and boiling heat transfer tests

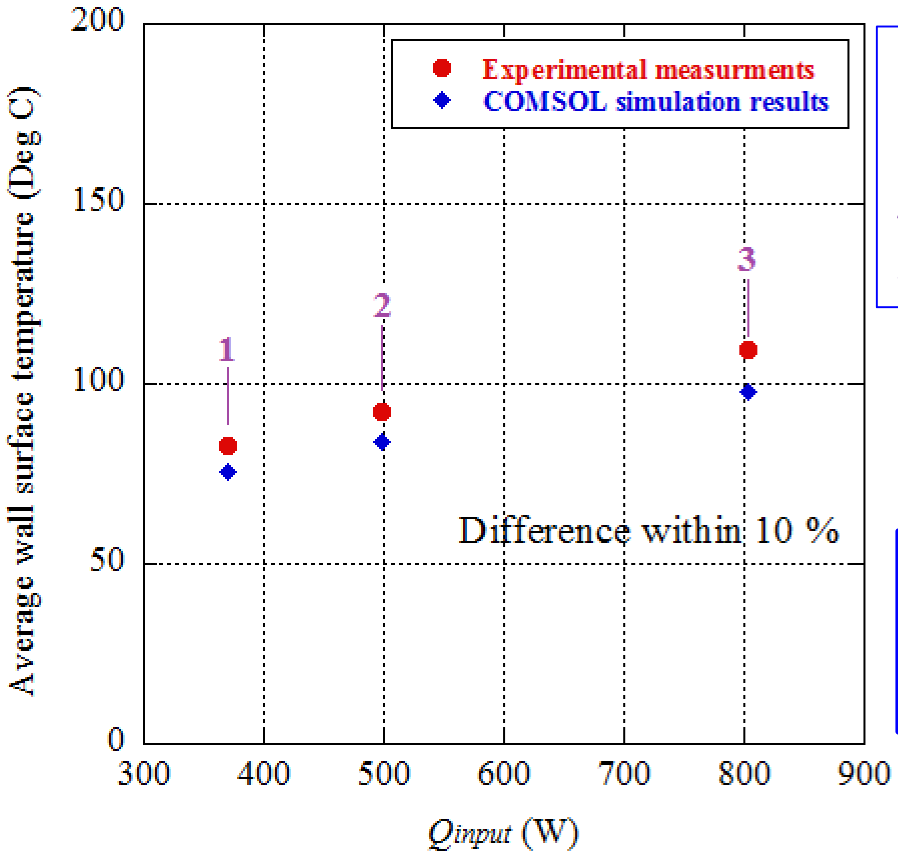


Heat loss is well characterized

Technical Accomplishments -- FY15

Preliminary test for laminar flow in the cooling channel

- Experiment test conditions
  - ✓ Coolant: 50/50 EG/W mixture
  - ✓ Flow velocity: 0.04 m/s



Coolant flow average temperature, T_f:

1 - 68.9 C

2 - 74.0 C

3 - 81.3 C

Simulation predictions agree with the measurement results for single phase laminar flow in the Toyota Prius power electronics cooling channel

Collaborations/Interests

- APEEM/ORNL
  - ✓ For information exchange of power electronics cooling
  - ✓ For power electronics cooling system module
  - ✓ For next step testing of coolant subcooled boiling cooling of power electronics in HEVs or EVs
- Dana Corporation
  - ✓ Initial discussions on heavy-duty markets, light-duty markets, and thermal management
- Bergstrom
- Eaton Corporation
  - ✓ Waste heat recovery for heavy-duty engines

Future Work

- Rest of FY15
  - ✓ Measure the subcooled boiling heat transfer coefficients in the cooling channel under various *steady state* conditions:
    - Various heat flux
    - Flow velocity
    - Coolant inlet temperature
    - High pressure (~2 atm)
  - ✓ Develop predictive models for subcooled boiling heat transfer coefficients based on experimental data
  - ✓ Compare and refine the simulation results

Demonstrate the technology on an actual power electronics cold plate under steady state conditions

- Beyond FY15:
  - ✓ Investigate the applicability of the technology under transient conditions (motor/inverter) to simulate vehicle drive cycles

Summary

- Relevance
  - ✓ Use subcooled boiling in the cooling channel to enhance the cooling of vehicle power electronics for HEVs and EVs
  - ✓ Eliminate the second cooling system
  - ✓ Apply to high power density electronics -- 200-250 W/cm^2 heat flux
- Approach
  - ✓ Perform numerical heat transfer modeling and simulations
  - ✓ Conduct experimental measurements
- Technical Accomplishments
  - ✓ Analyzed benefits of subcooled boiling over currently used convective heat transfer
  - ✓ Investigated effects of various parameters (flow velocities, coolant inlet temperatures, heat fluxes, etc.) on subcooled boiling of 50/50 EG/W coolant
  - ✓ Modified the heat transfer test facility and integrated the power electronics heat sink module into the test loop for evaluating the performance of subcooled boiling heat transfer
  - ✓ Preliminary experiments data collected

Summary (cont.)

- Collaborations
  - ✓ Ongoing efforts with APEEM team & ORNL for power electronics cooling system module
- Future Work
  - ✓ Measure the subcooled boiling heat transfer coefficients
  - ✓ Compare and refine the simulation results
  - ✓ Develop predictive models for subcooled boiling heat transfer coefficients based on test data
  - ✓ Demonstrate the subcooled boiling technology for power electronics cooling in HEVs to eliminate the low temperature radiator
  - ✓ Investigate the applicability of the technology under transient conditions to simulate vehicle drive cycles

Technical Back-Up Slides

Background: Current research and technologies for power electronics cooling system

- Liquid-cooled heat sinks with fin structure *(Bennion, K., Kelly, K., NREL 2009)*
  - ✓ Use of fins in the cooling channel to remove the heat
  - ✓ Need for second radiator to reduce the coolant inlet temperature
- Single-phase or two-phase jet impingement *(Narumanchi, S. et al., NREL 2005, 2008; Garimella, S.V. et al., Purdue University 2013)*
  - ✓ Removal of large, concentrated heat fluxes
  - ✓ Hardware for impingement
  - ✓ High flow velocity required
  - ✓ Stress concentration in the impingement zone
- Two-phase spray cooling *(Bharathan, D. et al., NREL 2005, 2008)*
  - ✓ Removal of large amount of heat flux
  - ✓ Need for a condenser to condense the vapor
  - ✓ Need for a pump to pressurize the liquid to form the spray
- Immersion pool boiling *(Moreno et al., NREL 2011)*
  - ✓ Need for separate pumping system for condensing vapor

Background: Current research and technologies for power electronics cooling system

- Single-phase jet impingement *(Narumanchi, S. et al., NREL 2005)*

	Glycol-water mixture		Water	
	90 W/cm^2	200 W/cm^2	90 W/cm^2	200 W/cm^2
Jet velocity, m/s	8	20	8	20
T_{inlet}, °C	105	105	105	105
T_{max}, °C	125	135	119	127
h_{copper}, W/m^{2}K	39,000	75,700	74,200	157,300
$h_{aluminum}$, W/m^{2}K	19,800	40,500	37,100	76,500

Heat Transfer Coefficient Model for Simulations

Subcooled Boiling Heat Transfer Coefficients

- <u>Shah Correlation (1977)</u>:

$$h_b = \dot{q}''/(T_w - T_f) = \dot{q}''/[(T_w - T_{sat}) + (T_{sat} - T_f)] = \dot{q}''/(\Delta T_{sat} + \Delta T_{sub})$$

$$\Delta T_{sat} = \dot{q}''/(\psi h_l)$$

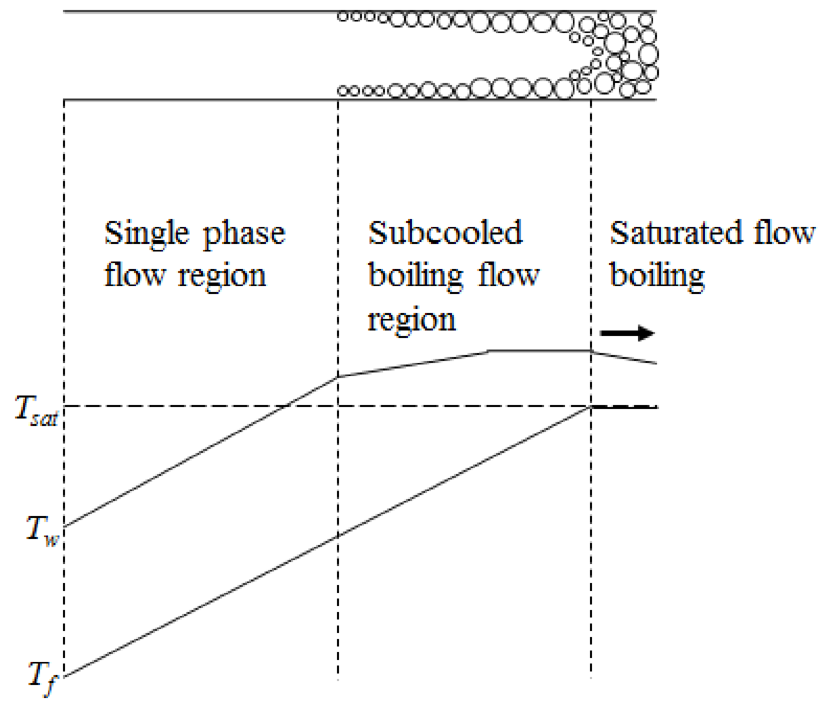
$$h_l = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4}(k/d)$$

$$\psi = \begin{cases} \psi_o & low\_subcooling\_region \\ \psi_o + \Delta T_{sub}/\Delta T_{sat} & high\_subcooling\_region \end{cases}$$

$$\psi_o = \begin{cases} 1 + 46 Bo^{0.5} & Bo < 3\times10^{-5} \\ 230 Bo^{0.5} & Bo > 3\times10^{-5} \end{cases}$$

Here, *Bo* is the boiling number

$$Bo = \frac{\dot{q}''}{G h_{fg}}$$



Challenges and Barriers

- High coolant temperature, 105 C -- eliminate the second radiator for HEVs

✓ Reduce the weight and cost of the vehicles

- Junction temperature control ≤ 175 C

✓ Improve the efficiency and lifetime of electronic components

- Applications of high power density electronics

  ✓ Wideband-gap semiconductor based power electronics (heat flux: 200-250 W/cm^2)

  - Coolant outlet temperature below the saturation point

  ✓ No vapor in the rest of the system

  ✓ Simple cooling system configuration