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

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Sponsored by L. Slezak (Vehicle Systems)

Project ID: VSS132

Overview

Timeline

- Project start date – FY14
- Project end date – FY15
- Percent complete – 25%

Barriers

- Weight – eliminate the second radiator for HEVs
- Performance and lifetime of electronic components – temperature
- Efficiency – junction temperature control
- Applications – high power modules for HEVs & EVs (e.g., wideband gap semiconductors)

Budget

- Total project funding (to date): $150K
- Funding received prior to FY14: $0K
- Funding for FY14: $150K

Partners

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

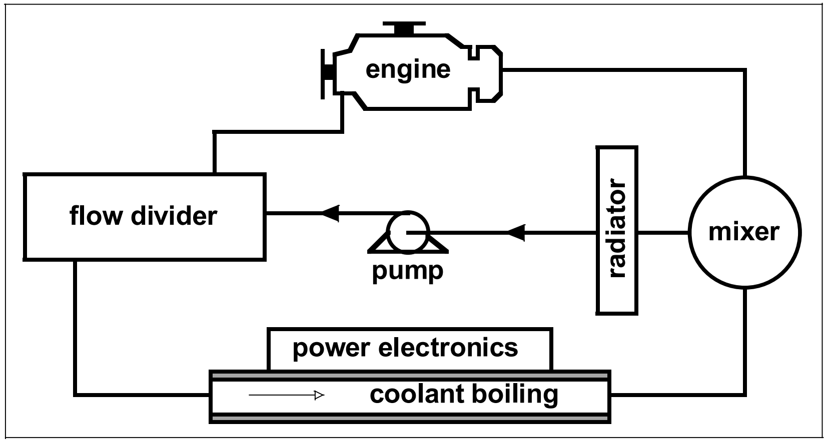
Relevance

- 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)

Delphi inverter

Relevance/Objectives

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



Objectives:

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

Addresses Targets:

- Eliminating the low-temperature cooling system for HEVs -- reduce the cost and weight.
  - ✓ Reduced pumping power and parasitic losses
- Using nucleate 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 nucleate boiling over currently used convection heat transfer.
  - ✓ Investigate various parameter effects on nucleate 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.
  - ✓ Measure nucleate flow boiling heat transfer coefficients under vehicle power electronics cooling conditions and compare with simulation results.
  - ✓ Develop predictive models for the nucleate boiling heat transfer coefficient for power electronics geometry cooling systems.

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

Approach - Milestones

Month/ Year	Milestone or Go/No-Go Decision	Description	Status
Mar./ 2014	Milestone	Numerical heat transfer simulations (COMSOL)	Completed
Oct./ 2014	Milestone	Design and modify the heat transfer test facility to integrate a power electronic module (inverter) in the current nucleate boiling loop	On-going
Mar./ 2015	Milestone	Measure nucleate boiling heat transfer coefficients for a typical power electronic module	Will be done
June/ 2015	Milestone	Develop predictive models for the nucleate boiling heat transfer coefficient based on the experimental data for power electronics geometry cooling systems	Will be done

Technical Accomplishments:

Key Conditions of Nucleate Boiling Simulations

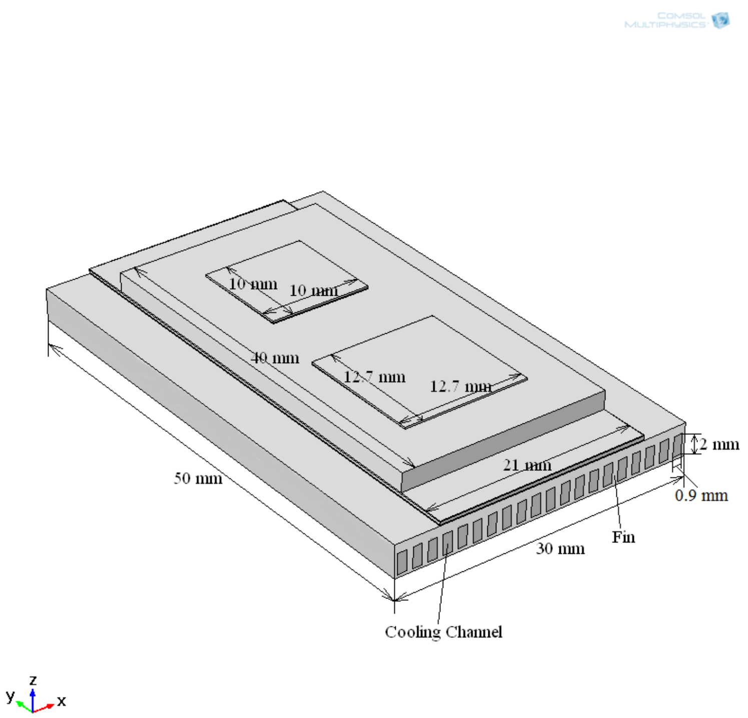
- Use of conventional engine coolant -- 50/50 ethylene glycol/water (EG/W) mixture
- Coolant fluid inlet temperature of 105 ˚C -- using engine cooling pumping system
- Flow velocity around 0.16 m/s (laminar flow)
  - ✓ Lower pressure drops and pumping power requirements
- Coolant fluid outlet temperature 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)

Nucleate boiling

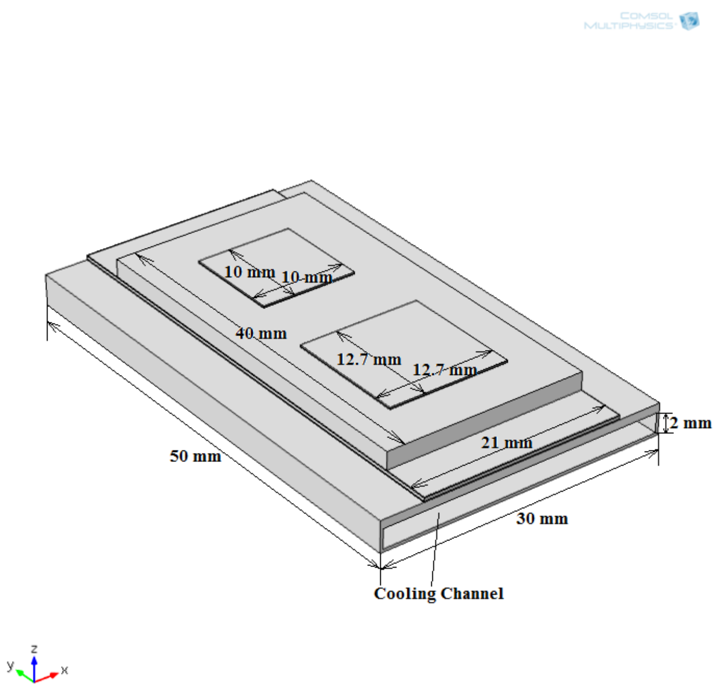
Technical Accomplishments:

Modeling Geometry of Nucleate Boiling Simulations

- Two models:



(a) With fins

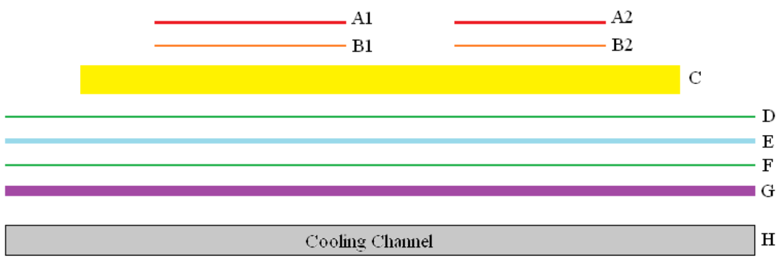


(b) Without fins

- Finned channel configuration -- current cooling systems
- No-fin channel configuration -- for reduction in capital cost and pumping power

Technical Accomplishments:

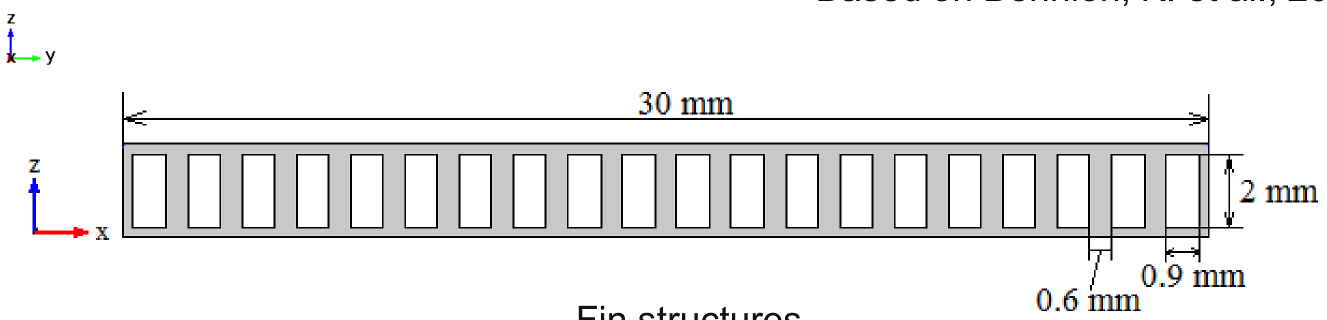
Materials and Dimensions of Each Component



Side view of each piece of power electronics and cooling channel

Index	Material	*x* (mm)	*y* (mm)	*z* (mm)
A1	IGBT: Si	12.7	12.7	0.145
A2	Diode: Si	10.0	10.0	0.145
B1	Solder	12.7	12.7	0.076
B2	Solder	10.0	10.0	0.076
C	Heat spreader: Cu	21.0	40.0	1.85
D	TIM: Thermal grease	21.0	50.0	0.1
E	Substrate: SiN	21.0	50.0	0.3
F	TIM: Thermal grease	21.0	50.0	0.1
G	Heat sink: Al	30.0	50.0	0.6
H	Cooling channel	30.0	50.0	2.0

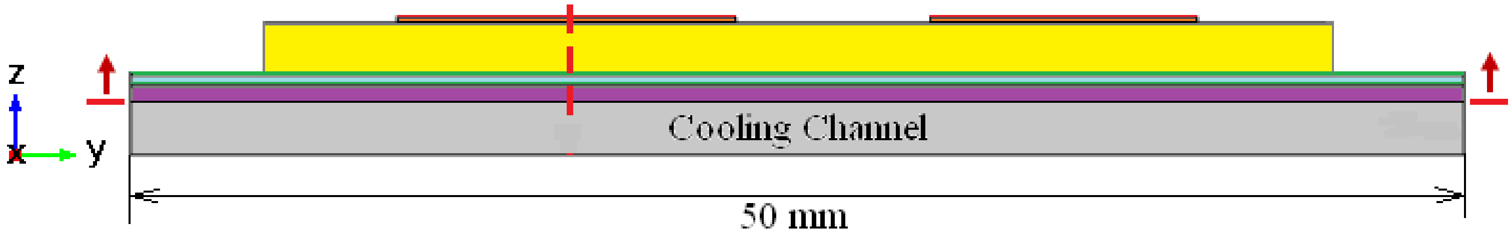
Based on Bennion, K. et al., 2009



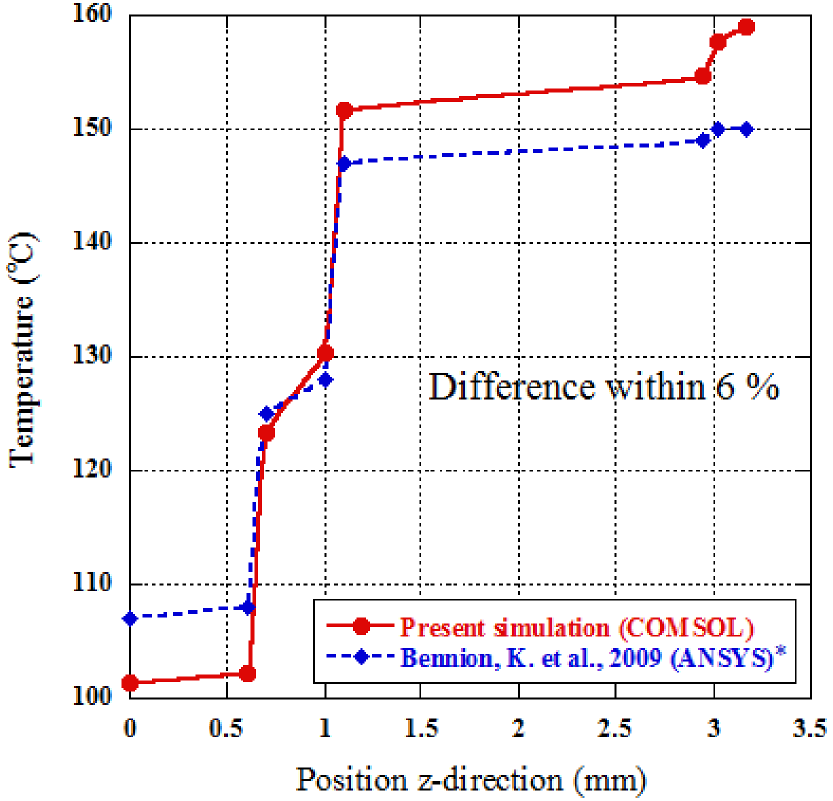
Fin structures

Technical Accomplishments:

Verification of Simulation Model (Single-Phase Flow)



Modeling geometry



- Comparison of the temperature profile
- $T_{coolant}$ = 70 ˚C
- IGBT heat flux: 93.2 W/cm^2
- TIM: 1.5 W/m·K
- h = 1877 W/m^2·K

* Bennion, K., Kelly, K., Rapid modeling of power electronics thermal management technologies, National Renewable Energy Laboratory, Center for Transportation Technologies and Systems, Golden, Colorado, Presented at the 5th IEEE Vehicle Power and Propulsion Conference, Dearborn, Michigan, September 7-11, 2009.

Technical Accomplishments:
Heat Transfer Coefficient Model of Nucleate Boiling Simulations

- Shah, M.M. (1977) Correlation:

$$h_b = \dot{q}'' / (\Delta T_{sat} + \Delta T_{sub})$$

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

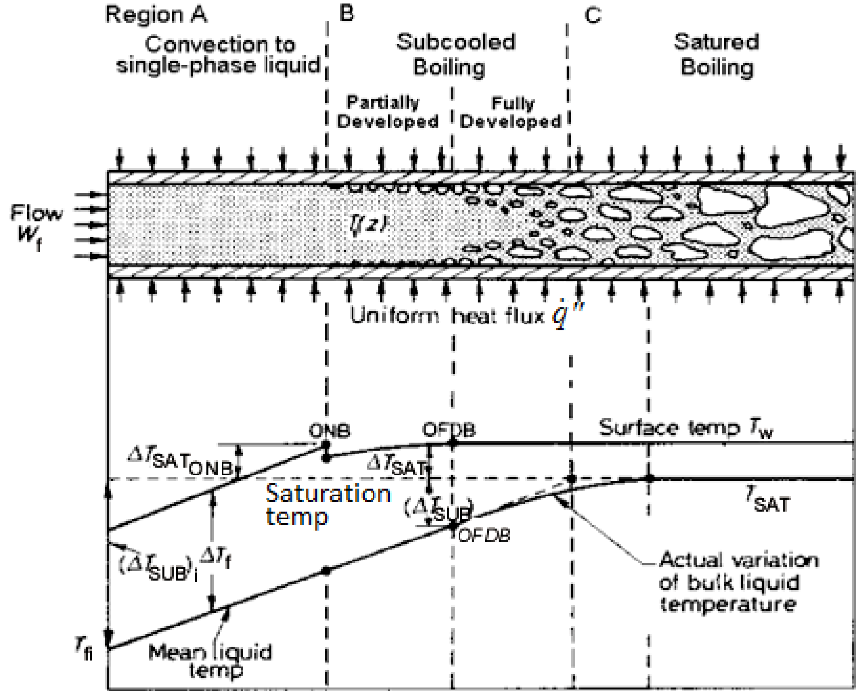
$$h_l = 0.023 \,\mathrm{Re}^{0.8}\, \mathrm{Pr}^{0.4} (k/d)$$

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

$$\psi_o = \begin{cases} 1 + 46 Bo^{0.5} & Bo < 3 \times 10^{-5} \\ 230 Bo^{0.5} & Bo > 3 \times 10^{-5} \end{cases}$$

Here, *Bo* is the boiling number

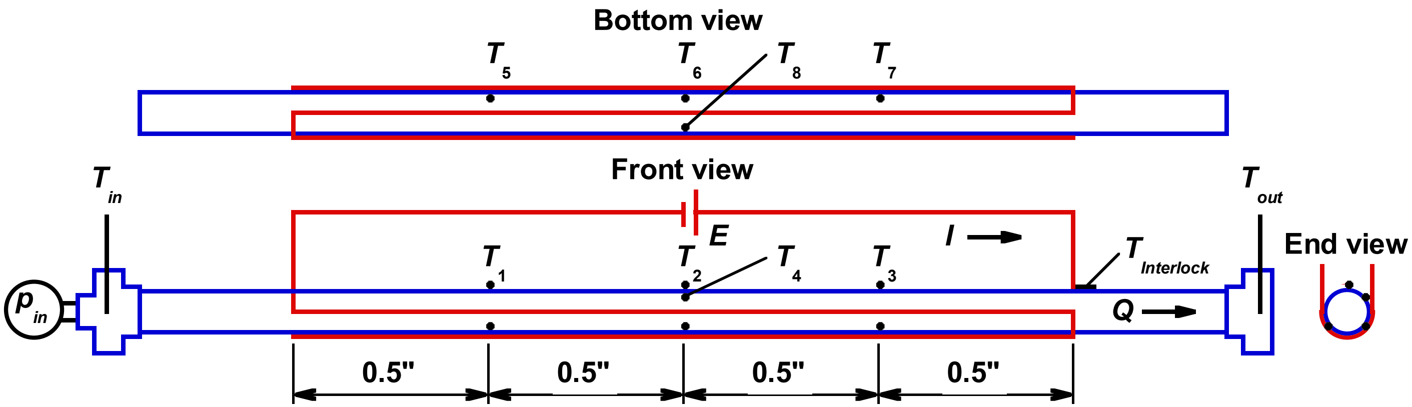
$$Bo = \frac{\dot{q}''}{G h_{fg}}$$



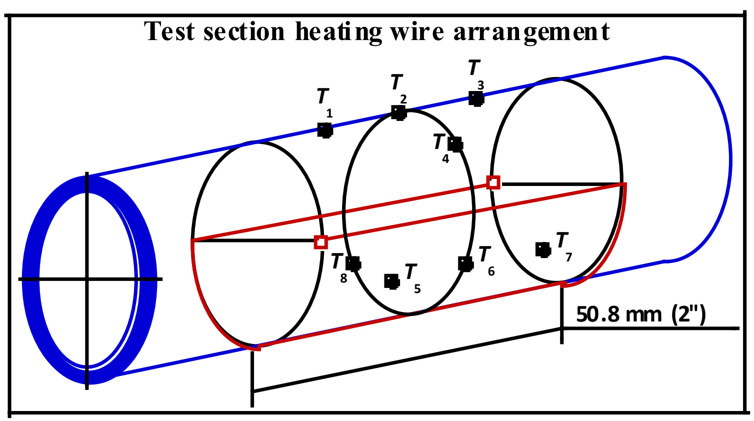
From: Alfredo José Alvim de Castro et al., 2001.

Technical Accomplishments:

Verification of Nucleate Boiling Heat Transfer Coefficient Model

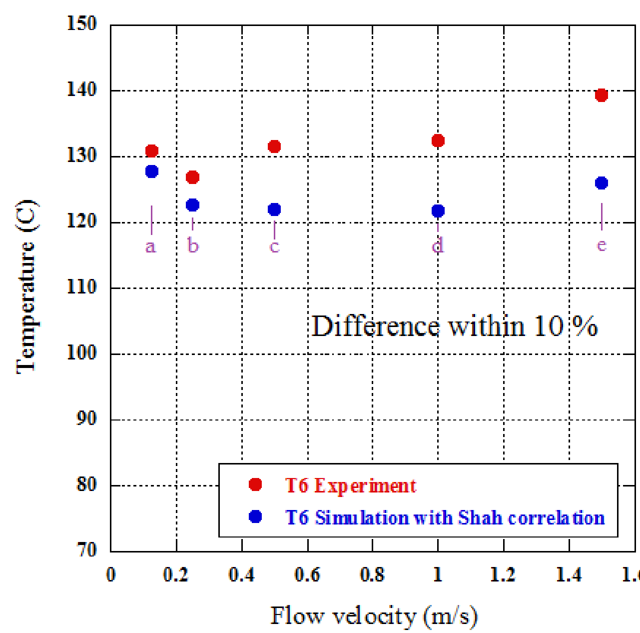


Heat transfer test section



Test section tube

Outer diameter of the tube: 12.7 mm (0.5")
Inner diameter of the tube: 10.9 mm (0.43")



T_{flow} = 97 °C
a - Q_{input} = 89.0 W
b - Q_{input} = 65.0 W
c - Q_{input} = 87.7 W
d - Q_{input} = 90.9 W
e - Q_{input} = 111.6 W

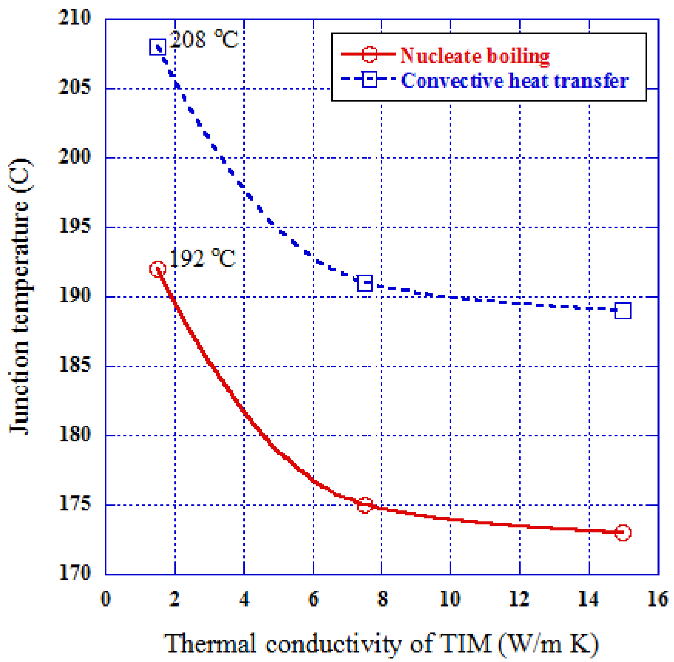
Comparison between experiment and Shah correlation

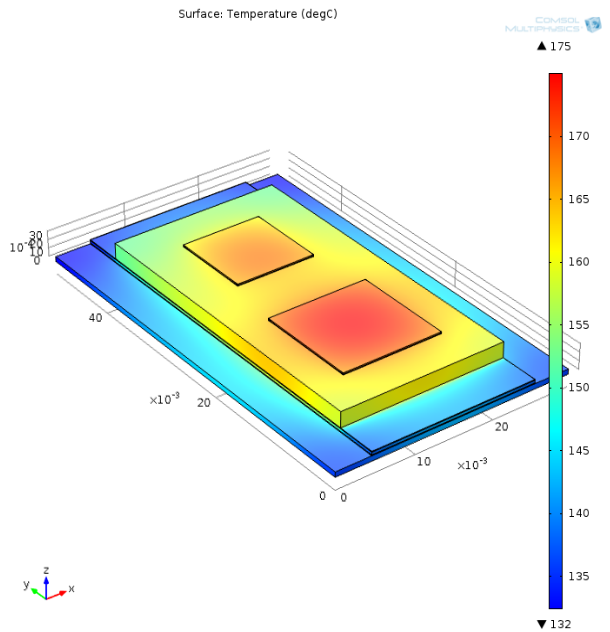
Experimental results agree quite well with predictions for two phase nucleate boiling

Technical Accomplishments:

TIM Effects on Nucleate Boiling

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





Nucleate boiling with 7.5 W/m·K TIM

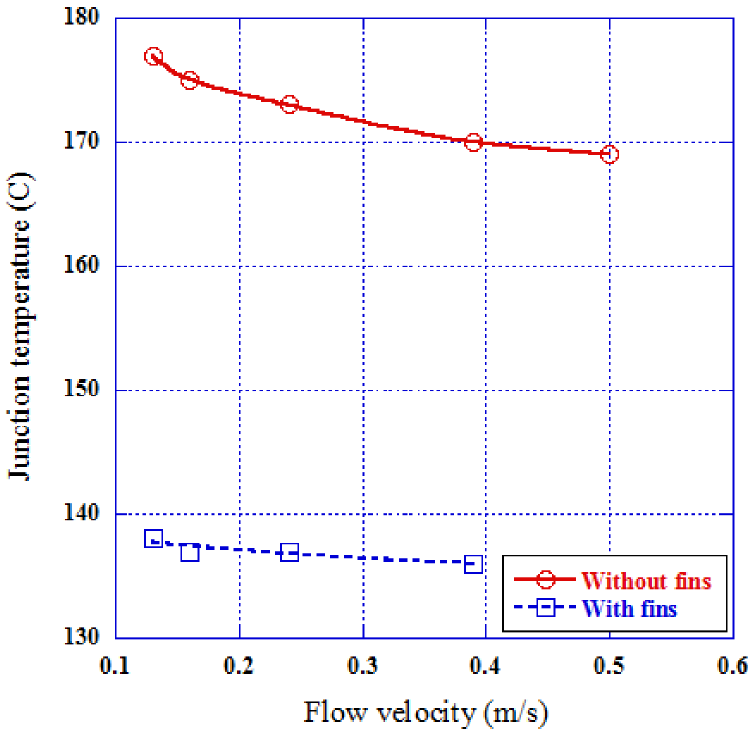
- The TIM thermal conductivity of 5 times that of the base case is sufficient.
- Nucleate boiling with a 7.5 W/m·K TIM can control the junction temperature under 175 ˚C.
- Fins can be eliminated in double-sided nucleate boiling cooling.

- Various thermal conductivities of TIM:
  - 1.5 W/m·K
  - 7.5 W/m·K
  - 15 W/m·K

Technical Accomplishments:

Coolant Flow Velocity Effects on Nucleate Boiling

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

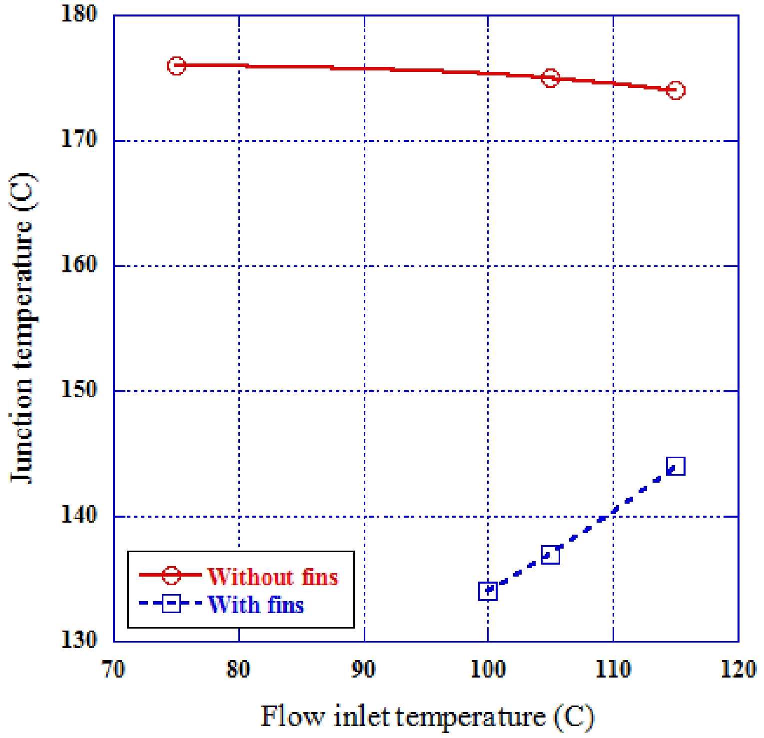


- Coolant flow velocity range: 0.06 m/s - 0.4 m/s (100 W/cm^2 heat flux with fins)
  - ✓ Coolant flow outlet temperature below the saturation point
  - ✓ Nucleate boiling range

- Efficient nucleate boiling cooling occurs at low flow velocities.
- Retaining fins with nucleate boiling reduces the junction temperature below 140 ˚C.
- The flow velocity does not have significant effects on nucleate boiling cooling.

Technical Accomplishments:
Coolant Flow Inlet Temperature Effects on Nucleate Boiling

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

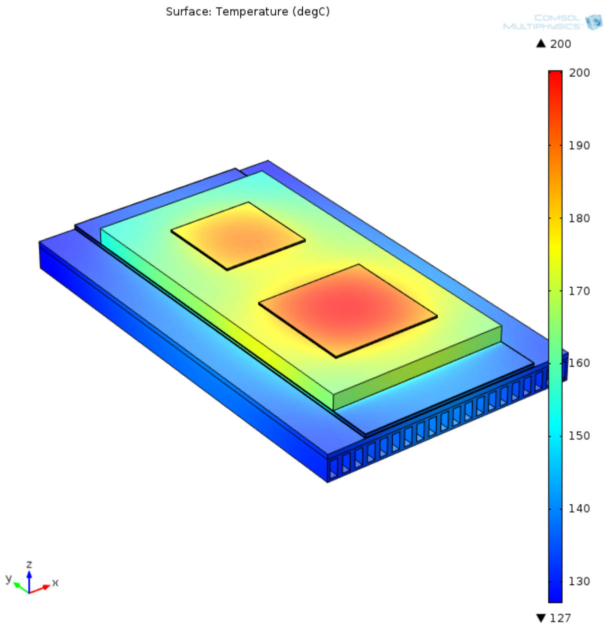


- With fins, coolant flow inlet temperature cannot be below 100 ˚C.
- ✓ Wall temperature is below the nucleate boiling range.
- ✓ Nucleate boiling is unlikely to occur.

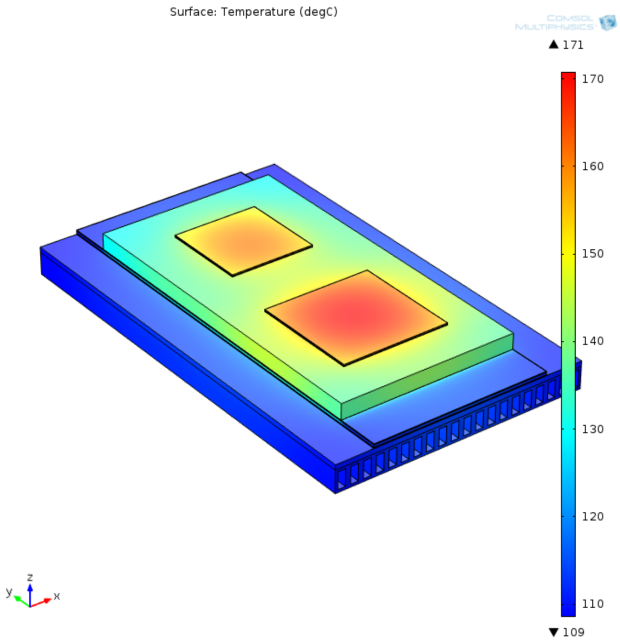
- Without fins, the junction temperature is below 175 ˚C, insensitive to the coolant temperature.
- With fins, the junction temperature is below 150 ˚C.

Technical Accomplishments:
High Heat Flux (Wideband Gap Semiconductors) Applications

- Double-sided cooling with a 7.5-W/m·K TIM for a 250-W/cm^2 heat flux



(a) Convective heat transfer



(b) Sub-cooled nucleate boiling

- Without nucleate boiling, the junction temperature is 200 °C.

- Nucleate boiling can reduce the junction temperature to <175 °C.

- Nucleate boiling can increase the cooling rate by 25% as compared to the current technology based on convective heat transfer.

Technical Accomplishments:
Comparison of Convection and Nucleate Boiling

• TIM - 7.5 W/m·K	Nucleate 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 nucleate boiling can cool current systems.
- With fins, nucleate boiling can increase the cooling rate by 25% or reduce the junction temperature.
- With fins, double-sided nucleate boiling can cool wideband gap semiconductors up to 250 W/cm^2.

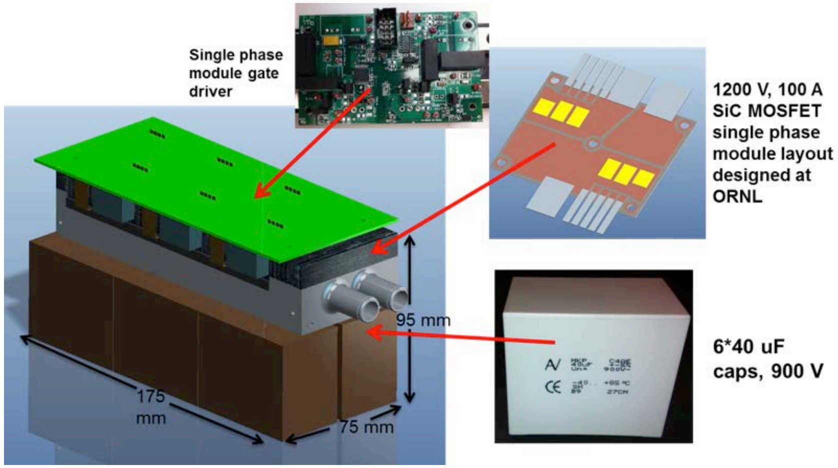
Collaborations

- APEEM/ORNL

  ✓ For information exchange of power electronics cooling

  ✓ For power electronics cooling system module

  ✓ For next step, testing of coolant nucleate boiling cooling of power electronics in electric vehicles



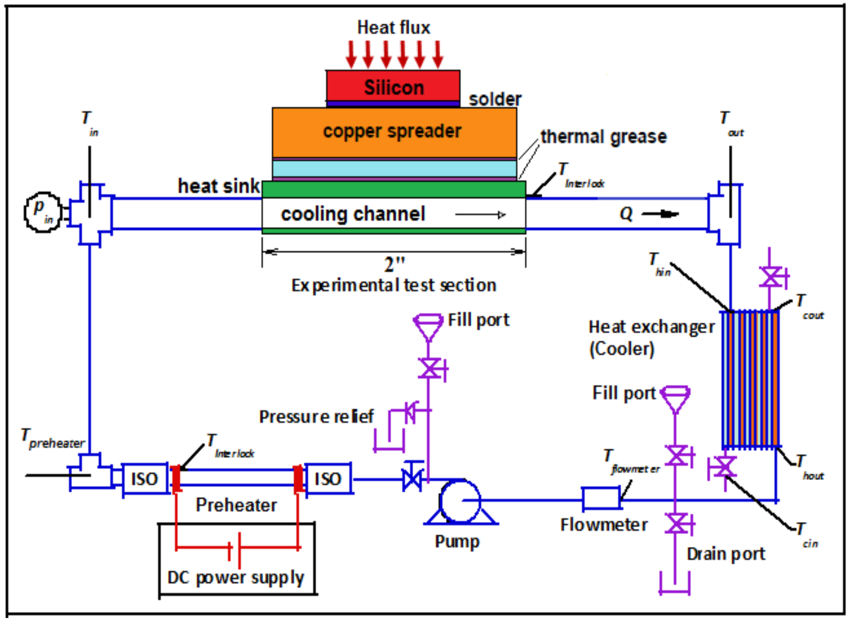
Courtsey: B. Ozpineci/ORNL

Future Work

- Rest of FY14
  - ✓ Design the nucleate boiling test section.
  - ✓ Collaborate with ORNL for the power electronics cooling system module.
  - ✓ Integrate the cooling module with the current fluid pumping system.
  - ✓ Run the nucleate boiling test under power electronics cooling channel conditions.

- FY15
  - ✓ Measure the nucleate boiling heat transfer coefficients in the cooling channel.
  - ✓ Develop predictive models for nucleate boiling heat transfer coefficients based on the experimental data.
  - ✓ Refine results of power electronics nucleate boiling cooling simulation.

- Next Step
  - ✓ Evaluate power electronics nucleate boiling cooling system in typical drive cycle conditions.
  - ✓ Collaborate with industries for technology transfer.



Schematic of the heat transfer test section

Summary

- Relevance
  - Uses nucleate boiling in the cooling channel to enhance the cooling of vehicle power electronics for HEVs and EVs.
  - Eliminates the second cooling system.
  - Applies 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 nucleate boiling over currently used convection heat transfer.
  - Investigated various parameter effects on nucleate boiling.

Summary (cont.)

- Collaborations

- Ongoing efforts with APEEM team & ORNL for power electronics cooling system module.

- Future Work

- Design and modify the heat transfer test facility simulating vehicle power electronics cooling conditions.
- Measure the nucleate boiling heat transfer coefficients.
- Develop predictive models for nucleate boiling heat transfer coefficients based on the test data.

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