Power Electronic Thermal System Performance and Integration

2009 DOE Vehicle Technologies Annual Merit Review

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Project ID: ape_13_bennion
Overview

Timeline
• Project Start: FY 2007
• Project End: FY 2011
• Percent Complete: 50%

Budget
• Total Funding (FY07-FY09)
  • DOE: $1,005K
  • Contract: $0K
• Annual Funding
  • FY08: $280K
  • FY09: $375K

Partners/Collaboration
• Electrical and Electronics Technical Team (EETT)
• USCAR Partners
• Delphi

Barriers
• Cost ($/kW)
• Specific Power (kW/kg)
• Power Density (kW/L)
• Efficiency
• Life
Objectives

- Facilitate the integration of APEEM thermal control technologies into commercially viable advanced automotive systems including hybrid electric, plug-in hybrid electric, and fuel cell vehicles
Objectives: Relevance

Thermal management directly relates to improvements in cost, power density, and specific power.

**Impacts: Lower cost, volume, and weight**
“easy ways to increase output power are paralleling more silicon chips and/or step-up the die size to increase current capacity. But this strategy is *unaffordable* in terms of both increased chip cost and packaging space”

**Enabling technology: double-sided cooling package**
“the most significant concern for increasing current is intensified *heat dissipation*”

*Source: Yasui, H., et al, “Power Control Unit of High Power Hybrid System” – Denso and Toyota, EVS23*
Milestones (FY08 & FY09)

FY08
Report on status and results of the thermal control technology R&D (September 2008):

- Developed an FEA parametric model and analysis techniques to characterize the thermal response of power semiconductor package designs.
- Developed techniques for characterizing vehicle drive profiles and PE thermal duty cycles in the frequency domain.
- Established industry relationships to study potential for double-sided cooling.

FY09
Evaluate cooling requirements for advanced power electronics topologies (June 2009).

Report on status and results of the thermal control technology R&D (September 2009).
Approach

1) Evaluate Tradeoffs for Improved Thermal Management.
   - Develop rapid screening tradeoff analysis tools.
     - Heat flux, heat exchanger performance, parasitic power.
   - Evaluate application to advanced power electronic thermal management packages.
   - Extend application to other critical components.

Why Important?
- Optimize thermal control package to meet performance targets.
Approach

2) **Characterize Thermal Impedance and Dynamic Loading.**
   - Characterize transient thermal impedance for package configurations and cooling techniques.
   - Utilize available in-use drive data from Vehicle Systems Analysis Technical Team to characterize in-use dynamic loading.

**Why Important?**
- Evaluate lightweight packages and support thermal stress and reliability comparisons.
Technical Accomplishments

Semiconductor Thermal Package Design Study

• Added new parametric 3D-FEA thermal modeling capability to understand the interactions between package topology, material selection, package size, and cooling technologies.

• Impact
  • Provides a modeling framework with the ability to simultaneously study the impacts of heat exchanger performance, material properties, and package geometry.
  • Integrates multiple avenues of thermal management technologies.

\[ T_f = 70^\circ C : \text{Substrate } k = 170 \text{W/m-K} \]

![Graph showing total heat flux dissipated vs. DBC offset with different heat transfer coefficients.](image)

Notes: Listed offsets were applied around the IGBT and diode. Items highlighted in brackets were variables in the analysis.
Technical Accomplishments

Semiconductor Package Thermal Performance Integration

- Matches thermal performance to the desired application and matches the cooling strategy to the selected power module packaging configuration.

- Impact
  - Meets the need to rapidly screen and compare multiple packaging and thermal management options.
  - Rapidly evaluates trade-offs associated with alternative packaging configurations and thermal management technologies.
  - Includes the integration of available experimental correlations, computational fluid dynamics results, parametric 3D FEA thermal models, and established heat exchanger analysis techniques.
  - Brings industry feedback into developed analysis techniques through close industry interaction.

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Technical Accomplishments

Semiconductor Package Thermal Performance Matching (Example)

Real $R_{th}$

[Effectiveness-NTU Method]

$$R_{th,NTU} = \frac{1}{\varepsilon \dot{m} c_p c_t}$$

Package specific thermal performance curves.

Heat Exchanger $R_{th}$ (C/W)

Heat Exchanger and Package Thermal Performance

[example: IGBT Heat Flux (W/cm²)]

- 40°C Coolant In
- 70°C Coolant In
- 105°C Coolant In
Technical Accomplishments

Power Electronics System and Capacitor Thermal Analysis

- Developed a parametric finite-element model for thermal control of power electronics at the module level.

- Impact
  - Includes thermal impact of key supporting components.
  - Performed preliminary investigation into the impacts of coolant temperature, heat exchanger performance, and capacitor cooling on the capacitor temperature profile.
  - Supports future work at system level.

- Developed parametric finite-element capacitor thermal model.
  - Variable CAD Geometry.
  - Variable material properties and boundary conditions.

- Impact
  - Supports future work related to capacitor thermal management.
Technical Accomplishments

Package Transient Response Characterization

• Demonstrated a method for comparing transient thermal impedance based on the frequency response of the power semiconductor package.

• Impact
  • Transient thermal impedance impacts package reliability.
  • Links the thermal duty cycle load in the frequency domain to the frequency response of the package.
  • Enables rapid transient simulations and quick qualitative comparisons.

• Future
  • Augment the technique through improved hardware validation and investigate how different cooling techniques impact the transient thermal response.
Future Work

- Apply modeling methodology to develop innovative thermal management package for power electronics applications enabling reductions in cost, weight, and volume targets.
  - Apply techniques to DOE and industry development technologies and leverage partner data to validate process.

- Improve research and development tasks related to thermal management technologies.
  - Research targets.
  - Integrate technologies.
  - System Impacts.

- Evaluate integration of power electronics thermal management system within a larger vehicle thermal management system context.
  - Leverage Vehicle Systems Analysis and Energy Storage groups.
Summary

System Thermal Performance and Integration is a Multi-Dimensional Problem

Vehicle Type
- HEV/PHEV
- FCV

Component Use
- Peak
- Continuous
- Dynamic

Cooling System
- Coolant Temperature
- Convection Coefficient
- Heat Exchanger Effectiveness

PE Package
- Topology
- Materials

• Accomplishments address multi-dimensional aspect of problem.

• Work is supported by industry and benefits from close industry interaction.

• Deliverables support and improve existing research and development efforts.

• Plan for future work leverages existing activities at DOE and industry partners.