Integrated Power Module Cooling

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Overview

Timeline

Project Start Date: FY 2012
Project End Date: FY 2013
Percent Complete: 75%

Budget

Total Project Funding:
DOE Share: $750K (FY12-FY13)
Funding Received in FY12: $350K
Funding for FY13: $400K

Barriers and Targets

• Cost
• Weight
• Volume
• Performance (Power Density)

Partners

• Interactions/collaborations
  – Sapa
  – Oak Ridge National Laboratory
• Project lead
  – National Renewable Energy Laboratory
Synthesis Partners Projected Inverter Cost Drivers to 2016

Relevance

Improved heat dissipation is needed to increase power for robust operation within cost and size constraints.
Objectives

- Cost
  - Improve power per die area with comparable or better power density
  - Low cost, scalable, and low waste manufacturing methods
- Volume
  - Maintain equivalent or better power density
- Weight
  - Eliminate large cast heat exchangers
- Reliability
  - Remove internal fluid seals to reduce leak-induced failure modes
  - Increase passive thermal stack thermal capacitance for transient heat loads
## Milestones

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
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| September 2011  | Milestone  
• Patent application submitted                                                                                                           |
| February 2012   | Go/No-Go  
• Computer simulations of heat spreader design matched preliminary analysis expectations.  
• Proceeded to hardware prototype design for targeted convective cooling performance.   |
| September 2012  | Milestone  
• Completed prototype design iterations through computational fluid dynamics modeling, balancing fabrication cost and thermal performance. |
| February 2013   | Go/No-Go  
• Validated models and confirmed prototype heat exchanger hardware matches design performance from modeling and analysis. |
| September 2013  | Milestone  
• Report on hardware validation of model results and demonstration of application to power semiconductor package cooling. |
Approach/Strategy

<table>
<thead>
<tr>
<th>2012</th>
<th>2013</th>
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<tbody>
<tr>
<td>Oct</td>
<td>Nov</td>
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Model Validation

- Complete experimental and hardware test setup
- Validate model fluid and thermal performance

Investigate heat exchanger surface design improvements in collaboration with industry partners

Legend

| Complete | In Progress |

(1) Go/No-Go

Model matches test results

(2) Go/No-Go

Investigate application and redesign for semiconductor package in collaboration with industry and laboratory partners

Sufficient data for industry transition
Approach/Strategy

- Heat Spreader Optimization (FEA)
- Develop Fin Geometry (CFD)
- Build, Test Prototype
- Confirm System Impact

FEA: Finite Element Analysis
CFD: Computational Fluid Dynamics

Photo Credits: Kevin Bennion, NREL
Technical Accomplishments and Progress

Insulated gate bipolar transistor (IGBT) heat flux comparison of preliminary heat spreader design showing target heat exchanger operating region

* All packages are compared based on single – sided cooling for consistency.
+ Subsequent heat spreader designs increased performance beyond 100% to meet design objectives.
Technical Accomplishments and Progress

Current State-of-Art:
- Reduce resistance by removing layers
- Require increasingly aggressive cooling techniques (potentially expensive)
- Rely on one-dimensional (1D) heat transfer through the stack

Conceptual Thermal Design:
- Enables multi-dimensional heat transfer
- Utilizes multiple cooling “zones”
- Compatible with multiple heat exchanger fabrication methods and area enhancements
  - Current design focuses on extrusion processes
    - Reduced heat exchanger cost
    - Increased flexibility
- Supports single and double-sided cooling
- Integrates channels (reduces seals)
Technical Accomplishments and Progress

Heat exchanger, baseplate, and manifold are combined into a single part

Designed to be extruded, easily scalable, and allow double sided cooling with no modification to design

Significant redesign between heat exchangers ($$$$)

Integrated base plate, heat exchanger, and manifold

TIM: Thermal Interface Material
BIM: Bonded Interface Material

Photo Credits: Kevin Bennion, NREL
Designed under Sapa’s extrusion guidelines\(^1\)

- Extrusion cost and die stress are minimized by:
  - Use recommended wall thickness based on a circumscribed circle
  - Uniform wall thickness throughout the part
  - Larger 2mm channels, 3mm fins
  - Open “E-fin” design reduces number of voids from 12 to 3
  - Eliminate sharp corners

\(^1\) Sapa Design Manual, Sapa AB, Rosemont, IL, 2009
Technical Accomplishments and Progress

Validated heat exchanger modeling with experimental results.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Material</th>
<th>Pressure Difference</th>
<th>Temperature Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>Al 6061</td>
<td>&lt;8%</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Design</td>
<td>Al 6061</td>
<td>&lt;9%</td>
<td>&lt;0.4%</td>
</tr>
<tr>
<td>Design</td>
<td>Al 6063</td>
<td>&lt;8%</td>
<td>&lt;0.8%</td>
</tr>
</tbody>
</table>

Flow Rate: 0.034 – 0.1 kg/s (1.9 – 5.6 L/min)

Validated heat exchanger modeling with experimental results.

Discrepancy between Modeling and Experimental Results

Photo Credits: Kevin Bennion, NREL
Technical Accomplishments and Progress

Design meets >2x heat flux improvement at target flow rate (10 L/min split among 6 branches)

- Baseline increases coefficient of performance (COP) by a factor of 4.1 at same flow rate as Lexus*
- Proposed design increases COP by a factor of 7.9 at same flow rate as Lexus*
- Design gives additional 12% performance increase relative to baseline at equivalent parasitic fluid power (system flow rate of 10 L/min split between 6 branches)
- Compatible with double-sided cooling and bus bar cooling

*Estimated at 0.0086 kg/s per side of package
Technical Accomplishments and Progress

Heat density increased by 34% (Exceeded Objective) over Lexus at target flow rate (10 L/min split among 6 branches)

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- Proposed design increases COP by a factor of 7.9 at same flow rate as Lexus*
- Design gives additional 12% performance increase relative to baseline at equivalent parasitic fluid power (system flow rate of 10 L/min split between 6 branches)
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*Estimated at 0.0086 kg/s per side of package
Collaboration and Coordination

Other Government Laboratories

Oak Ridge National Laboratory/APEEM Program
- Support from benchmarking activities
- Ensure thermal design space is appropriate and modeling assumptions are consistent with other aspects of APEEM research

Industry

Heat Exchanger Collaboration Partner (Sapa)

Power Semiconductor Packaging Partner Input

Plan

Model Validation

Investigate heat exchanger surface design improvements

Investigate application and redesign for semiconductor package in collaboration with industry and laboratory partners
## Future Work

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### Future Work:
- Investigate heat exchanger surface area enhancement design improvements and incorporate lessons learned from initial prototype fabrication.
- Investigate application to specific semiconductor package with industry input.

- **The project is scheduled to end in FY13**
- **Future work:**
  - Investigate heat exchanger surface design improvements in collaboration with industry partners.
  - Investigate application and redesign for semiconductor package in collaboration with industry and laboratory partners.
Summary

Relevance

- Increased heat dissipation is necessary to reduce power semiconductor cost, weight, and volume.
- Integration of the power electronics package, thermal design, and the cooling design can improve power semiconductor performance.
- A modular and scalable thermal approach can reduce the need for custom heat exchanger redesigns as applications scale in power.

Approach/Strategy

- Reduce cost by increasing semiconductor heat flux at equivalent or smaller volume
- Reduce cost by enabling less aggressive and lower cost cooling methods
- Enable compatibility to alternative power semiconductor packaging technologies

Technical Accomplishments

- Built three prototype designs and validated model results against experimental results
- Met or exceeded project design targets

Collaborations

- Established collaboration with heat exchanger development partner (Sapa)
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