Power Electronics Cooling for Automotive Applications

Progress Report

Desikan Bharathan
Outline

• Objectives
• Methods
  • Indirect and direct jet cooling
  • Direct spray cooling
  • Spreaders
• Development of models & example results
• Next steps
• Conclusions

June 7-9, 2004
DOE Program Review
The Need

Cooling needs for automotive applications consist of:
   a) predominantly engine cooling
   b) cabin a/c systems
   c) other auxiliary systems

   With the advent of electric hybrids, we add:
      d) power electronics

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The Sink

Ultimate sink for the heat is the ambient air! Heat is rejected via sensible heat.
(is latent heat an option? – perhaps not)

Performance is tied to ambient temperature.
System must accommodate hottest climates.
The Load

Typical load consists of dominantly:

- Engine (120kW) ➔ 120 kW (cooling)

Other Minor Loads

- A/C (3kW; COP 1.5) ➔ ~5 kW
- Power Electronics ➔ ~2-5 kW
The Cooling Circuit

Most vehicles are “water-cooled.” A coolant (EG 50% in water) carries heat from the engine block to a radiator.

T~105°C
Cooling Power Electronics - Characteristics

- Cooling needs are small
- Heat is generated in localized
- Heat generation is highly transient
- Spots with low thermal capacities show large local temperature swings
Power Electronics Cooling

• Independent loop:
  – May be cooled using an independent loop (because of small loads), however, this approach requires more components

• Using engine coolant:
  – This approach forces the incoming coolant temperature to 105°C, thus making the cooling system design difficult
Objective

Explore the use of jet and spray cooling techniques through simulation and experiments toward achieving the programmatic goals
Program Goals

- To achieve a heat flux of 250 W/cm\(^2\), at a coolant temperature of 105°C
- To maintain chip source temperature of less than 125°C
- To meet other requirements on reliability, safety and cost

These requirements translate to an overall heat-transfer coefficient of 125,000 W/m\(^2\)K.
FY04 completed activities

- Literature review performed
- Modeling capabilities evaluated
- Numerical models developed for jet and sprays
- Validated some models under specific conditions
- Commercial CFD code modified for specific needs
Technical Approaches

• Direct Cooling
  – Cooling fluid is directly in contact with the heat source
  – Fluid must be electrically non-conducting, e.g., Air, CO₂, He, or Fluorinert (FC-72)

• Indirect Cooling
  – A cooling plate acts as a barrier between the heat source and the coolant, coolant can be glycol mixture or any other fluid
## Direct Cooling

### Examples:

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Potential HTC (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air (Nat. Conv)</td>
<td>20 - 40</td>
</tr>
<tr>
<td>Air (Forced)</td>
<td>40 - 80</td>
</tr>
<tr>
<td>Refrigerated Compressed Air</td>
<td>80 - 120</td>
</tr>
<tr>
<td>Fluorinert (FC-72)*</td>
<td>1000 - 2000</td>
</tr>
</tbody>
</table>

*Its low thermal conductivity and heat of vaporization limits HTC;*
Indirect Cooling

In this approach, we introduce more resistances in series.

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# Indirect Cooling

## Potential Performance (SOA)

<table>
<thead>
<tr>
<th>Component</th>
<th>Conductivity (W/mK)</th>
<th>Thickness (µm)</th>
<th>HTC (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Interface Material</td>
<td>2</td>
<td>20</td>
<td>100,000</td>
</tr>
<tr>
<td>Plate (Al)*</td>
<td>165</td>
<td>6350</td>
<td>25,000</td>
</tr>
<tr>
<td>Coolant (EG mixture)</td>
<td>0.342</td>
<td>1 mm jet; sprays</td>
<td>100,000</td>
</tr>
</tbody>
</table>

*Spreading will increase its effective conductivity*
Indirect Cooling

SOA

\[ R_{\text{TIM}} = 0.1 \]
\[ R_{\text{Plate}} = 0.4 \]
\[ R_{\text{Coolant}} = 0.1 \]

We are at least a factor of six below the programmatic goal;

Bottleneck being the mounting plate (the thickness is perhaps governed by structural reasons)

Overall \( U = 16,700 \text{ W/m}^2\text{K} \)

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NREL Research Efforts

- Direct cooling using FC-72
  - Jet impingement
  - Spray cooling
- Indirect cooling (with antifreeze mix)
  - Jet impingement
    - Spent liquid removal
Background - Jets

• Substantial number of works are reported on jet impingement, micro channel, and heat transfer
• Key correlations are provided by Garimella (1996)
• Optimization methods are summarized by Lin and Vafai (1999)
• Key findings are that:
  – submerged jets perform better than free-surface jets
  – effective removal of spent liquid is essential
Direct jet impingement

- Minimum residence time is ~0.01s;

- Maximum is well over 20 times the minimum, showing large recirculation zones

- Spent liquid removal is key to maintain high heat transfer coefficients

*FC-72 jet, Garimella, et. al, 1996
Indirect cooling
Semikron’s baseline cold plate
Cold plate temperatures

$q' = 40 \text{ W/cm}^2$;

$T_{\text{coolant}} = 70 \degree \text{C}$;
Improved pin-fin design – rev. 1

Baseline

Recommended

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Cold plate temperatures

Baseline

Recommended

An 8°C improvement

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Indirect jet cooling; temperatures – rev 2

Each jet is directed at each hot spot; Spent liquid is removed via a central outlet.
Spent liquid recirculates!
Indirect jet cooling – rev 3
Section via plane through outlet
Exploded view of the cavities
Temperature distributions

$q' = 84 \text{ W/cm}^2$;

$T_{\text{coolant}} = 105 \degree \text{C}$;
Flow paths and residence times

$V = 10 \text{ m/s};$

$T_{\text{min}} = 1.8 \text{ ms};$

Spent liquid removal is more effective;
Spray cooling

Keith Gawlik
Why consider direct spray cooling?

- Eliminates all interface material between source and sink
- Makes a variety of fluids available for use
- Makes heat flux potentially more uniform than with jets
- Supports the program goal to improve heat transfer and reduce cost and complexity

- However, the physics of sprays are very difficult to capture in numerical and analytical models
First model development

- Geometry and operating conditions based on published experimental work (Purdue)
- 11 W/cm$^2$ at 10$^\circ$ DT, 0.76 lpm, FC-72
- Our first simulation used current CFD capabilities
Spray model - Temperatures

FC-72 spray

$q''_{avg} = 12.4 \text{ W/cm}^2$

at 10° DT
Heat flux variation across surface of 30° segment

Region of low droplet density

Region of high droplet concentration

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CFD spray modeling capabilities

- Different modes of interactions between particles and surfaces are possible:
  - wall jets and films: either single phase heat transfer or limited phase change allowed
  - particle trapping: complete evaporation

- Particle trapping mode is considered similar to physical behavior at high heat fluxes
Multiple sprays

- Simulates specific hardware
- Components mounted inside housing with four nozzles, and two outlets
- Each nozzle cools a single hot spot
- Heat flux from chips 83.4 W/cm²
- Modified CFD code used
Spray flow geometry

Chips mounted inside housing opposite nozzles

Housing
Animated Spray
Enabling Technologies

- Heat spreaders, including heat pipes
- Improved thermal interface materials
- Surface enhancements
- Heat pumping
  - using waste heat
  - using auxiliary refrigeration system
  - using thermoelectrics
Heat Spreaders*

*Simons, R.E., Electronics Cooling, 2004
Influence of Spreader Conductivity

- 7x7 mm heat source; 84 W/cm²; Spread angle 45°; Coolant at 106°C; h-eff = 100,000
<table>
<thead>
<tr>
<th>Approach</th>
<th>Advantages</th>
<th>Disadvantage</th>
<th>Technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct cooling</td>
<td>Eliminates many intermediaries between source and sink</td>
<td>Non-conducting liquids are necessary; Coatings are possible; pulsed jets possible;</td>
<td>Jets</td>
<td>Very high heat transfer coefficients are possible</td>
<td>Potential for erosion exists</td>
<td>Submerged jets are preferred</td>
</tr>
<tr>
<td>Sprays</td>
<td>Offers gentle contact with the heat source</td>
<td></td>
<td></td>
<td>Model difficulty is severe; requires testing and verifications; requires filtering</td>
<td></td>
<td>Model difficulty is severe</td>
</tr>
<tr>
<td>Indirect Cooling</td>
<td>Use of conventional coolants is possible</td>
<td>Additional barriers such as spreader plate and TIM are introduced</td>
<td>Jets</td>
<td>Very high heat transfer coefficients are possible; submerged jets are preferred; Can handle impurities;</td>
<td>Potential for erosion exists</td>
<td>Can benefit from improved heat spreader, TIM, surface enhancement and other technologies</td>
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</tr>
<tr>
<td>Microchannels</td>
<td>Requires only small volumes; is readily modeled.</td>
<td></td>
<td></td>
<td>Requires effective filtering</td>
<td></td>
<td>Model difficulty is severe</td>
</tr>
</tbody>
</table>
Next steps

- Continue improving simulation approaches for jets and sprays
- Investigate the use of micro-channels
- Model heat transfer cases for actual hardware
- Compare and validate model with experimental data
- Investigate other enabling technologies
System level approaches may yield larger benefits

- System studies to assess cost benefit of independent loop
- Cost tradeoffs on miniaturization of chips
- Use of PCM or other means to increase local thermal capacity to reduce transient temperature swings
Conclusions

• Jet and spray models offer means to improve hardware designs
• Spray models require substantial empirical data on interactions
• Experimental verification of models for specific hardware are needed in collaboration with industry