Introduction

DS&A LLC:

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David L. Saums, Principal

Thirty-four years of electronics thermal management business development, strategic planning, market assessment, product development management, and technical marketing.

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Organizing Committee, Technical Session Chair, IMAPS France ATW Thermal (2006-2012)  
Member:  IMAPS, IEEE, SAE, PSMA

IMAPS Fellow (2010)
Global use of liquid cooling for electronics systems:

- Pervasive
- Evaluated and implemented globally in certain market segments for 50+ years:
  - Electrical transformers and systems components for traction (1910)
  - Power electronics systems (1960)
  - Computing systems (1966)
  - Semiconductor testing (1970)
  - Computing systems – refrigeration (1997)
- Multiple technologies and methodologies implemented in production systems:
  - Single-phase EGW/PGW (water/glycol)
  - Two-phase sealed (water) heat pipes and thermosyphons; other fluids
  - Two-phase with dielectric liquids for liquid immersion
  - Dielectric liquids for spray cooling
  - Pumped refrigerants
  - Refrigeration
Liquid Cooling Systems for Electronics Thermal Management

Global base of experienced manufacturers of liquid cooling systems/components for electronics:

- Large vendor base with many suppliers and wide range of capabilities and costs
- Engineering factors:
  - System performance, heat flux, volume reduction, reliability, product life, ambient temperature, acceleration, mounting attitude, other requirements
  - Fluid performance, type, temperature range, filtering requirements, sealant requirements, life and breakdown characteristics, dielectric value, deionization replenishment, other.
- Significant business factors determine use of liquid cooling and the potential for adoption of different technologies:
  - Company entrenched liquid cooling engineering knowledge base:
    - Typically single-phase
    - Minimal two-phase experience
  - Cost drivers
  - Logistics requirements (field service training, field service, component interchangeability, fluid handling, fluid safety)
Liquid Cooling Systems for Electronics Thermal Management – New Market Drivers

New markets and market needs are driving continued developments in thermal management, including liquid cooling systems and fluids:

- **Vehicle** electrification for HEV/BEV drivetrains
- Battery technologies and energy storage
- Data center output, physical volume and location, and efficiency
- Wind turbines
- Solar power conversion
- Transmission
Global demand for rapid improvements in energy efficiency in every form is driving rapid development in the power semiconductor market – and thermal materials and solutions:

- All forms of energy generation, transmission, storage, application.
- Power semiconductor fabrication: transition from silicon to silicon carbide:
  - Higher temperature capability with smaller semiconductor footprint
  - Reduced device size, reduced losses
  - Higher reliability, improved life
- Power semiconductor packaging development requirements:
  - Packaging and thermal materials
  - Components
  - Power delivery, storage, and thermal management components and systems
- Higher temperature capability for semiconductor devices:
  - SiC may be used at current operating temperatures to achieve higher system reliability.
  - SiC may be used at higher future operating temperatures, with accompanying demand for higher system reliability.
- Summary: Higher operating temperatures, heat fluxes, requiring new packaging materials and improved thermal management solutions.
Trends in IGBT Module Performance and Reliability Improvement

- IGBT module packaging improvements:

<table>
<thead>
<tr>
<th>IGBT Module Packaging Improvements and Needed Development Materials and Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>© Copyright 2012 DS&amp;A LLC</td>
</tr>
<tr>
<td>Higher-temperature packaging and thermal materials</td>
</tr>
<tr>
<td>Low-temperature joining materials and processes</td>
</tr>
<tr>
<td>Transition to improved wirebonding techniques (e.g., wedgebonding)</td>
</tr>
<tr>
<td>Transition to monolithic module metals (e.g., copper; aluminum)</td>
</tr>
<tr>
<td>Transition from aluminum wire to aluminum ribbon bonding</td>
</tr>
<tr>
<td>Higher thermal conductivity CTE-matched baseplate materials</td>
</tr>
<tr>
<td>Double-sided liquid cooling package developments</td>
</tr>
<tr>
<td>Two-phase and dielectric immersion liquid cooling developments</td>
</tr>
</tbody>
</table>
## Military Ground Vehicle HEV Powertrain Thermal Management

US Army ground mobile vehicle overall powertrain thermal management system goals:

<table>
<thead>
<tr>
<th>Ground Mobile Vehicle Powertrain Thermal Management Key Goals</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power electronics coolant temperature (inlet)</td>
<td>65°C (baseline)</td>
</tr>
<tr>
<td>Power electronics heat flux</td>
<td>80°C (threshold)</td>
</tr>
<tr>
<td></td>
<td>100°C (objective)</td>
</tr>
<tr>
<td>Air filtration scavenging blower performance</td>
<td>2X improvement (motor service life)</td>
</tr>
<tr>
<td></td>
<td>89 W/cm² (baseline)</td>
</tr>
<tr>
<td></td>
<td>350 W/cm² (threshold)</td>
</tr>
<tr>
<td></td>
<td>400 W/cm² (objective)</td>
</tr>
</tbody>
</table>

*Source: RDECOM TARDEC*
# Vehicle Onboard Coolant Choices and Temperature Ranges: HEV/PHEV/EV

<table>
<thead>
<tr>
<th>Vehicle PEEM Cooling Technology</th>
<th>Coolant Maximum Temperature (Typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forced Air</td>
<td>60°C</td>
</tr>
<tr>
<td>Separate Liquid Cooling Circuit</td>
<td>65 - 80°C</td>
</tr>
<tr>
<td>Engine Liquid Cooling Circuit</td>
<td>95 - 105°C</td>
</tr>
<tr>
<td>Transmission Oil Cooling Circuit*</td>
<td>125°C</td>
</tr>
</tbody>
</table>

* Typically used only for motor stator cooling in HEV powertrain

Source: After I. Graf, Infineon Technologies

IMAPS Chesapeake Symposium
March 14, 2012

Overview: Liquid Cooling Systems for Electronics

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Military Ground Vehicle HEV Powertrain Thermal Management

Brief examples of component development to meet new requirements for IGBTs for HEV developments – single-phase liquid cooling:

Source: Wolverine Tube LLC
Military Ground Vehicle HEV Powertrain Thermal Management

Brief examples of component development to meet new requirements for IGBTs for HEV developments – single-phase liquid cooling:

*Source: Wolverine Tube LLC*
Military Ground Vehicle HEV Powertrain Thermal Management

Brief examples of component development to meet new requirements for IGBTs for HEV developments – single-phase liquid cooling:

Internal all-copper pin array developed using innovative copper machining process (monolithic copper structure, zero scrap, multidimensional pin structures for flow optimization)

Source: Wolverine Tube LLC
SiC Power, RF Module, and Energy Storage Thermal Management Developments

Clockwise from upper right: CTE-matched thermal core PCB developments with high thermal conductivity for RF devices; Energy storage liquid cooling and materials developments; Monometallic IGBT module assembly (all-copper); GE Power Overlay (POL) SiC IGBT module aluminum-graphite liquid cold plate for high temperature control with direct liquid contact.

Sources: DS&A LLC, photographs; MMCC Inc.; Infineon Technologies
### Summary: Thermal Challenges for Power Semiconductors and Energy Efficiency

<table>
<thead>
<tr>
<th>Trend</th>
<th>Impact</th>
<th>Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of required electronic modules: placement underhood, on-engine, within nacelles</td>
<td>Increasing ambient operating temperatures</td>
<td>Higher-temperature materials (&gt;150-200°C and &gt;200-300°C)</td>
</tr>
<tr>
<td>More highly integrated components</td>
<td>Higher power losses</td>
<td>Improved joining and CTE-matched materials</td>
</tr>
<tr>
<td>More electrification</td>
<td>Increasing power requirements</td>
<td>Lower cost module-level liquid cooling solutions</td>
</tr>
<tr>
<td>Increasing switching speeds</td>
<td>Higher heat fluxes</td>
<td>Improved thermal joining materials</td>
</tr>
<tr>
<td>Double-sided liquid cooling</td>
<td>Reduced cost and volume</td>
<td>Improved liquid cold plate/immersion plate design</td>
</tr>
</tbody>
</table>

Source: DS&A LLC, after M. Rittner (Robert Bosch)
## What Does Industry Need?

<table>
<thead>
<tr>
<th>Simplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance targeted to market needs - <em>Not</em> maximum attainable research performance</td>
</tr>
<tr>
<td>Minimum total system and operating costs – <em>Not</em> minimum possible components cost</td>
</tr>
<tr>
<td>Reliable system performance targeted to application requirements</td>
</tr>
<tr>
<td>Speed and ease of system repair at minimum reasonable cost</td>
</tr>
</tbody>
</table>
Contact Information

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Tel: +1 978 499 4990
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Electronics thermal management market research, business strategy, and product strategy development.
Vaporizable Dielectric Fluid Cooling Systems for Electronics Thermal Management

David L. Saums, Principal
DS&A LLC, Amesbury MA USA
dsaums@dsa-thermal.com

Overview Presentation

IMAPS Chesapeake Chapter Symposium
University of Maryland USA
March 14, 2012
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IMAPS Fellow (2010)
Purpose and Motivation

Purpose:

1. Describe an innovative pumped two-phase liquid cooling system developed for power semiconductor thermal management. This system offers:
   - *Low pumping rate* two-phase cooling with a dielectric fluid as the coolant, a common refrigerant (R-134a).
   - Vaporizable Dielectric Fluid (VDF) systems are now shipping in commercial applications for electrical drives.

2. Illustrate system operation briefly.

3. Describe briefly several applications for this system.

Note: US and international patents have been applied for and/or granted to Parker Hannifin Corporation and Thermal Form & Function Inc., for the system concept and certain components of this two-phase liquid cooling system.
Liquid Cooling for Electronic Systems

Many different types of liquid cooling and vapor compression systems exist in the electronics market and have been used in some market segments for decades:

<table>
<thead>
<tr>
<th>Cooling System Type</th>
<th>Coolants</th>
<th>Primary Market Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-phase water</td>
<td>Tap water, chilled water</td>
<td>Industrial, commercial power electronics; ground vehicles; computing systems</td>
</tr>
<tr>
<td></td>
<td>Deionized water</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EGW, PGW (glycol, other antifreeze mixtures)</td>
<td>Industrial, commercial power electronics; ground vehicles; computing systems</td>
</tr>
<tr>
<td>Single-phase mil/aerospace</td>
<td>Dielectric liquids (3M Fluorinert™ liquids, Fluroketones; PAO; oils)</td>
<td>Military airborne, shipboard, ground systems</td>
</tr>
<tr>
<td>Two-phase water</td>
<td>Tap, chilled, deionized water</td>
<td>Industrial power electronics (including heat pipes); laboratory use and evaluation</td>
</tr>
<tr>
<td>Two-phase dielectric liquids</td>
<td>Dielectric liquids (3M Fluorinert™ liquids, Fluroketones), R-134a refrigerant</td>
<td>Computing, industrial power electronics</td>
</tr>
<tr>
<td>Liquid spray cooling</td>
<td>Dielectric liquids (3M Fluorinert™ liquids, Fluroketones), oils</td>
<td>Aerospace power supplies; computing</td>
</tr>
<tr>
<td>Liquid immersion</td>
<td>Dielectric liquids (3M Fluorinert™ liquids, Fluroketones); oils</td>
<td>Traction; Industrial mining vehicle powertrains; transformers; computing</td>
</tr>
<tr>
<td>Vapor cycle compression</td>
<td>Refrigerants, carbon dioxide</td>
<td>Military airborne electronics; semiconductor burn-in, test, validation; vehicle/HEV</td>
</tr>
</tbody>
</table>

Source: DS&A LLC
## Properties of Typical Electronic Coolants

<table>
<thead>
<tr>
<th>Coolant</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Thermal Expansion Coefficient (K⁻¹)</th>
<th>Specific Heat (J/kg-K)</th>
<th>Boiling Point (°C)</th>
<th>Freezing Point (°C)</th>
<th>Reference Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0.600</td>
<td>0.0003</td>
<td>4279</td>
<td>100</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>Ethylene Glycol/Water (50%)</td>
<td>0.404</td>
<td>0.0016</td>
<td>3341</td>
<td>107.2</td>
<td>-34</td>
<td>25</td>
</tr>
<tr>
<td>Propylene Glycol/Water (50%)</td>
<td>0.382</td>
<td>0.0023</td>
<td>3640</td>
<td>222</td>
<td>-28</td>
<td>25</td>
</tr>
<tr>
<td>3M™ Novec™ HFE-7100 (HFE)</td>
<td>0.069</td>
<td>0.0018</td>
<td>1183</td>
<td>61</td>
<td>&lt;-38</td>
<td>25</td>
</tr>
<tr>
<td>R-134a</td>
<td>0.0824/0.0145</td>
<td>N/A</td>
<td>1400</td>
<td>-26.1²</td>
<td>-103</td>
<td>25</td>
</tr>
</tbody>
</table>

**Note 1.** Vapor at 1 atm (101.3kPa), 25°C.  **Note 2:** Boiling point at 1 atm, 25°C.
<table>
<thead>
<tr>
<th>Coolant</th>
<th>GWP (GWP)</th>
<th>Flashpoint (°C)</th>
<th>Vapor Pressure (kPa)</th>
<th>Dielectric Constant (@1kHz)</th>
<th>Prandtl Number</th>
<th>Liquid Density (kg/m³)</th>
<th>Reference Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>0</td>
<td>None</td>
<td>3.2</td>
<td>78.5</td>
<td>6.2</td>
<td>997</td>
<td>25</td>
</tr>
<tr>
<td>Ethylene Glycol/Water (50%)</td>
<td>Low</td>
<td>111</td>
<td>2.3</td>
<td>N/A</td>
<td>29</td>
<td>1076</td>
<td>25</td>
</tr>
<tr>
<td>Propylene Glycol/Water (50%)</td>
<td>Low</td>
<td>99.1</td>
<td>N/A</td>
<td>N/A</td>
<td>46</td>
<td>1034</td>
<td>25</td>
</tr>
<tr>
<td>3M™ Novec™ HFE-7300</td>
<td>210</td>
<td>None</td>
<td>5.9</td>
<td>7.4</td>
<td>N/A</td>
<td>1660</td>
<td>25</td>
</tr>
<tr>
<td>R-134a</td>
<td>1300</td>
<td>None</td>
<td>661.9³</td>
<td>9.5</td>
<td>N/A</td>
<td>1210</td>
<td>25</td>
</tr>
</tbody>
</table>

Note 1: @150°C*  Note 2: Autoignition temperature shown.  Flash point: None.  Note 3: Vapor pressure, saturated liquid.  Note 4: @20°C.
Water-Based Coolants

Long recognized for high heat capacity as an electronic coolant. Significant issues for practical application in critical power electronics:

- Deionization is frequently required to eliminate chlorine and other ions and reduce risk of galvanic and other types of corrosion.
- Safety in the event of leak.
- Inability to use mixed metals in system.
- Frost proofing required - Addition of ethylene glycol (EG) or propylene glycol (PG) in mixtures to approximately 65%.
  - Toxicity (EG)
  - PG is more effective as a heat transfer agent than EG.
  - Increasing frostproofing additive percentage decreases fluid thermal performance.
- Other additives required based on fluid operating temperatures:
  - Corrosion inhibitors
  - Algaecides
  - Biocides
  - pH control
Refrigerants as Electronic Coolants

Common refrigerants such as R-134a and HFO-1234yf offer excellent properties for use as dielectric coolants for electronic systems:

- Compatible with a wide range of rubbers, polymers, and other sealant and tubing and insulating materials;
- Compatible with many engineered plastics
- Improved viscosity (with lubricant) versus water and EGW for microchannel and mesochannel construction;
  - Less propensity for bubble and other potential blockages
  - Used in a sealed system, not requiring periodic refilling. No potential for particulate entrance.
  - Thousands of components designed for refrigeration systems available globally.

Practical characteristics of refrigerants:

- Non-toxic and evaporates at room temperature, with no damage to electronics
- Available globally from many suppliers at reasonable cost
- For military ground vehicle applications: already in the military logistics pipeline.
- Stable and inert across a wide temperature range, not requiring frostproofing.
Refrigerants as Electronic Coolants - Concerns for ODP and GWP

Environmental concerns for refrigerants:
- Ozone Depletion Potential (ODP)
- Global Warming Potential (GWP)
- Primary target for change directives is mobile A/C for vehicles

HFO-1234yf refrigerant replacement for R-134a:

- Joint development program: Dupont, Honeywell
- "Drop-in" replacement for R-134a
- GWP value: 4
- Pilot production availability: 2010
- EU vehicle market phase-in: MY2012 target
### Mechanically Pumped Two-Phase Dielectric Fluid Cooling System Development

<table>
<thead>
<tr>
<th>Company</th>
<th>Coolant</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPFL (Lausanne, Switzerland)</td>
<td>R-134a, HFO-1234ze</td>
</tr>
<tr>
<td>USDOE Oak Ridge National Laboratory (US)</td>
<td>R-134a</td>
</tr>
<tr>
<td>Parker Hannifin Precision Cooling Business Unit (US)*</td>
<td>R-134a, HFO-1234yf</td>
</tr>
<tr>
<td>Raytheon Company (US)</td>
<td>R-134a</td>
</tr>
<tr>
<td>Thermal Form &amp; Function Inc. (US)*</td>
<td>R-134a, HFO-1234yf</td>
</tr>
</tbody>
</table>

* Commercialized systems
VDF Two-Phase Dielectric Fluid Cooling System Development

- 1999 - Initial development work for Pumped Liquid Multiphase Cooling (PLMC)
  - Thermal Form & Function Inc. (Manchester MA USA)
  - First prototype designs completed for:
    - Hewlett-Packard (Enterprise server cabinet)
    - Raytheon (phased array radar)
- 2007 - Joint development agreement with Parker Hannifin (New Haven IN USA):
  - Cooperative engineering development of systems concepts
  - Vaporizable Dielectric Fluid Cooling (VDF)
  - Joint development of principal components:
    - Pumps
    - Liquid cold plates
    - Manifolds
- January 2009 - First commercial system shipments
Use of a dielectric fluid with boiling significantly reduces the liquid flow rate required:

<table>
<thead>
<tr>
<th>Coolant (1 gram)</th>
<th>Coolant Temperature Increase</th>
<th>Flow Rate Required to Dissipate 1kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>5°C (9.0°F)</td>
<td>2.9 l/min. (46 gal./hr.)</td>
</tr>
<tr>
<td>R-134a (40°C*)</td>
<td>(Isothermal at 40°C*)</td>
<td>0.35 l/min. (5.8 gal./hr.)</td>
</tr>
</tbody>
</table>

*Note: Dependent upon system pressure. Fluid is R-134a or HFO-1234yf
Source: TF&F Inc.
VDF Two-Phase Dielectric Fluid Cooling Self-Optimizing System Operation

System concept is relatively simple but incorporates highly-engineered components:

- Pump, liquid cold plates, condenser
- Modular system design
- Highly scalable
- Typical heat removal: A mesochannel liquid cold plate with a 1kW load will remove heat fluxes approaching 900W/cm².
- Typical flow rates and pressures: 250lph@350kPa (50PSI) for 10KW system cooling.

Notable Reference:
Electronics Cooling Magazine (March 2011, pp. 22-27)
VDF Two-Phase Dielectric Fluid Cooling Self-Optimizing System Operation

VDF cooling system loop:
- Pressure and temperature are allowed to “float” relative to ambient conditions.
- System design target: System is designed for a known maximum power load at maximum ambient conditions.
- System design engineer may set the refrigerant saturation temperature by adjusting system operating pressure:
  - Adds additional degree of freedom for system design;
  - Higher pressure will increase saturation temperature, enabling a higher junction temperature and smaller condenser and/or lower airflow.
- Demonstrated thermal performance versus single-phase water cooling
- Low flow rates, low pressure drop.
- Multiple isothermal liquid cold plates connected in series or parallel.
- R-134a vaporizes on contact with electronics, non-toxic
- Ability to mix metals (copper cold plates, aluminum condenser) in a single system without concern for galvanic action.
- Refrigerant or other dielectric vaporizable fluid will tolerate extreme temperature extremes without frostproofing.
- Several different refrigerants are available globally for use in these systems.
- Heat exchanger (condenser) can be of any type.

Note: There is no compressor as these are not vapor-cycle compression systems.
Fluid considerations and compatible pumps:

- Thousands of R-134a compatible hoses, quick-disconnects, other components available in refrigeration and HVAC industries.
- Improved viscosity (with lubricant) versus water and EGW for microchannel construction;
  - Less propensity for bubble formation and other potential blockages
  - Sealed system, not requiring periodic refilling: no potential for particulate entrance
- Dielectric fluid pump flow-through designs:
  - All pumps designed with flow-through for winding/bearing lubrication and cooling
  - Lubricant (small percentage) used in dielectric fluid for pump lubrication
  - Lower pressure operation for improved $L_{10}$ life.
## VDF Two-Phase Dielectric Fluid Cooling Self-Optimizing System Operation

<table>
<thead>
<tr>
<th>17kW Pump Rated Performance</th>
<th>Unit</th>
<th>Value</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Fluid</td>
<td>N/A</td>
<td>R134a</td>
<td>-</td>
<td>R-134a</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>VDC</td>
<td>22-32</td>
<td>VDC</td>
<td>22-32</td>
</tr>
<tr>
<td>Rated Operation Pressure, Max</td>
<td>PSIA</td>
<td>310</td>
<td>Bar</td>
<td>21.38</td>
</tr>
<tr>
<td>Burst Pressure</td>
<td>PSIA</td>
<td>1550</td>
<td>Bar</td>
<td>106.90</td>
</tr>
<tr>
<td>Rated Pressure Rise, Continuous</td>
<td>PSID</td>
<td>50</td>
<td>Bar</td>
<td>3.45</td>
</tr>
<tr>
<td>Min Flow at Rated Continuous Operating Pressure</td>
<td>GPM</td>
<td>1.94</td>
<td>LPM</td>
<td>7.34</td>
</tr>
<tr>
<td>Intermittent Operating Pressure, Max</td>
<td>PSID</td>
<td>100</td>
<td>Bar</td>
<td>6.90</td>
</tr>
<tr>
<td>Maximum Fluid Temperature</td>
<td>°C</td>
<td>80</td>
<td>°C</td>
<td>80</td>
</tr>
<tr>
<td>Maximum Operating Ambient Temperature</td>
<td>°C</td>
<td>80</td>
<td>°C</td>
<td>80</td>
</tr>
<tr>
<td>Minimum Fluid Temperature</td>
<td>°C</td>
<td>-40</td>
<td>°C</td>
<td>-40</td>
</tr>
<tr>
<td>Minimum Storage Temperature</td>
<td>°C</td>
<td>-54</td>
<td>°C</td>
<td>-54</td>
</tr>
<tr>
<td>Weight, Approximate</td>
<td>Kg</td>
<td>2.72</td>
<td>Kg</td>
<td>2.72</td>
</tr>
</tbody>
</table>
VDF Two-Phase Dielectric Fluid Cooling Self-Optimizing System Operation

- 1-2: Sub-cooled fluid enters and flows through pump (100% liquid)
- 2-2': Liquid flow through tubing connecting pump to liquid cold plate
- 2'-3: Sensible heat transfer in liquid cold plate
- 3-4: Fluid flow boils to predetermined liquid/vapor percentage
- 4-5: Tubing from liquid cold plate to condenser
- 5-6: Condensing heat transfer to liquid: Vapor enters condenser where heat is released; vapor condenses to liquid
- 6-7: Subcooling: Sensible heat transfer, reducing temperature of liquid to ensure 100% liquid enters pump
- 7-1: Tubing from condenser to pump; cycle repeats

Source: TF&F Inc.
IMAPS Chesapeake Symposium
March 14, 2012

Overview: Liquid Cooling Systems for Electronics
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VDF Two-Phase Dielectric Fluid Cooling Self-Optimizing System Operation

- As the load decreases, the system boils less
- There are no penalties in this because fluid flows are low and pump parasitic power draw is low
- The system reacts quickly to varying power levels and fluid flow is constant

Source: TF&F Inc.   
IMAPS Chesapeake Symposium  
March 14, 2012
A two-phase dielectric fluid cooling system with multiple liquid cold plates allows either parallel or series construction:

- Cold plates operating in parallel, with a single condenser: All cold plates operate at the same temperature.
- Cold plates operating in series, with a single condenser: All cold plates will operate with only very modest changes in temperature and pressure.

- Example: 3 liquid cold plates with 34.5kPa (5 PSI) pressure drop, in series at 1kW power dissipated per cold plate
- Result is a 1.4°C decrease in saturation temperature.
Results

Case study - Improvements achieved with VDF cooling for AC variable speed drive design:

• Extremely high efficiency of two-phase heat transport
• Relatively low flow rates and low pressure drop
• Highly-scalable system design
• Multiple isothermal liquid cold plates
• Dielectric fluid eliminates concerns for mixed metals in a system
• Inert dielectric fluid is compatible with many hose, seal, and plastic materials
• Dielectric fluid can be used to cool and lubricate pump windings and bearings
• Series or parallel operation of liquid cold plates with no flow instability
• More power from same devices
  ▪ Increased power density, smaller foot print or both
  ▪ Prototype design goal achieved, system: 10kW power dissipation
  ▪ Production design, system: 20kW power dissipation
  ▪ Goal is full rated power at 50 – 55 deg C
• Increased switching frequency with no de-rating
• Improved overload ratings
• Potential to reduce silicon costs
Results

Source: Parker Hannifin

IMAPS Chesapeake Symposium
March 14, 2012
Production System Examples

Example 1 - Medium voltage electrical drive system with VDF cooling system:

System Pump Module (25LPH per kW of heat dissipated)

Production electrical drive cabinets (2)
Production System Examples

Example 1 - Medium voltage electrical drive system with VDF cooling system for variable speed motor drive applications:

- Total heat dissipation (system): 27kW
- Solution achieved with implementation of VDF cooling:
  - 20% cost reduction at the system level
  - System volume reduction of 25-50%
  - Reduction in number of IGBT modules used: 27 reduced to 18
  - Power density per rack increase: 300kW to 1MW per rack (3X)
### Production System Examples

**Example 2 - Medium voltage electrical drive system with transformer for variable speed motor drive applications:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline System Design</th>
<th>Replacement VDF System Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat dissipation (kW):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Transformer</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Coolant</td>
<td>Deionized water, deionization cartridge filters</td>
<td>MP two-phase R-134a</td>
</tr>
<tr>
<td>Coolant flow rate</td>
<td>System: 450GPM</td>
<td>System: 70GPM</td>
</tr>
<tr>
<td>Transformer only</td>
<td>225GPM</td>
<td></td>
</tr>
<tr>
<td>Pump weight</td>
<td>800 lbs.</td>
<td>65 lbs.</td>
</tr>
<tr>
<td>Cabinet size</td>
<td>84” H (multiple)</td>
<td>30% reduction (total system volume)</td>
</tr>
</tbody>
</table>

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Production System Examples

Example 3 - Containerized utility-scale backup power systems:
- Total heat dissipation (system): 350kw
- Solution achieved with implementation of VDF cooling:
  - Isothermal temperatures achieved across racks, system
  - Highly controlled interior ambient temperature conditions
Example 4 – Military ground vehicle HEV inverter

**Number of IGBTs**: 3

**Total Thermal Load**: 3 [kW]

**Net Thermal Resistance** *(from die to heat sink)*: 0.03 [C/W]

**Possible Die Temperature**: 83.36 [C]

**Exit Quality**: 70 [%]

**Ambient Temperature**: 35 [C]

**System Pressure Drop**: 25 [PSI]

**Pump Flow Rate**: 86.8 [l/hr]

0.3822 [gal/min]

Development System Examples

Example 4 – Military ground vehicle HEV inverter

Development System Examples

Example 4 – Military ground vehicle HEV inverter

Development System Examples

Example 5 – Power LED commercial projector

Completed LED projector mechanical prototype with PLMC cooling system

Three copper liquid cold plates mounting (3) PhlatLight LED modules. Each liquid cold plate is electrically isolated.

Luminus Devices “PhlatLight™” Power LED Module mounted on copper cold plate (x 3)

Total power dissipation for complete light engine: >200W (Typical)

Thermal resistance, sink-to-fluid: 0.025°C/W (Typical)
Current Applications

Current commercial, industrial, and military systems in production and in development:

- Industrial motor drives, UPS (uninterruptible power supplies) (27kW to 1MW, production)
- Large industrial transformers (development)
- Military ground vehicle HEV powertrain inverter (18-27kW, development)
- Naval shipboard power supply (1MW, development)
- Construction vehicle HEV powertrain ultracapacitor energy storage arrays (development)
- Enterprise servers (development)
- Blade and rack-mount servers (development)
- Projection system power LED light engine (development)
- Containerized power and data servers (development)
Summary

- Single-phase liquid cooling using water and other fluids is widely used with decades of deep electronics industry experience base in system and component design.
- Water is not an adequate coolant for power electronics thermal management.
- A “dielectric water” with excellent characteristics for heat capacity, boiling point, temperature tolerance, and zero cost would be ideal.
- A deep global experience base exists with dielectric fluids, including refrigerants.
- Two-phase *passive* liquid cooling (i.e., heat pipes) has achieved widespread use globally.
- Two-phase *pumped dielectric fluid* cooling system concepts have been developed for power semiconductor and digital electronic system thermal management.
  - System comparative testing has been performed for two-phase fluid cooling versus air and water-based cooling and presented.
  - System configurations with pumps, cold plates, manifolds, quick-disconnects are available.
  - These systems have now been commercialized.
Summary

- Practical two-phase mechanically-pumped dielectric fluid thermal management can enable significant improvements in overall system design:
  - Advanced thermal management solutions implement improvements in semiconductor device performance:
    - Substantially higher output current under system steady-state and overload conditions.
  - Large improvements in system performance with reduced semiconductor content and costs.
  - Large reductions in system complexity and volume.
  - Improvement in overall system-level cost, safety and failure protection, and reliability.
Summary

- Quote:

“Two-phase liquid cooling systems are complex only to non-specialists.”

- Jonathan Olivier
  Research Scientist, Laboratory of Heat and Mass Transfer
  Swiss Federal Institute of Technology (EPFL)
  Lausanne, Switzerland

NATO Specialists Meeting
System-level Electronics Thermal Management
Bucharest, October 6, 2010
Practical Thermal Management is One Component of System Solutions

<table>
<thead>
<tr>
<th>What Does Industry Need?</th>
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<tbody>
<tr>
<td>Simplicity</td>
</tr>
<tr>
<td>Performance targeted to market needs - <em>Not</em> maximum attainable research performance</td>
</tr>
<tr>
<td>Minimum total system and operating costs – <em>Not</em> minimum possible components cost</td>
</tr>
<tr>
<td>Reliable system performance targeted to application requirements</td>
</tr>
<tr>
<td>Speed and ease of system repair at minimum reasonable cost</td>
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Electronics thermal management market research, business strategy, and product strategy development.