Parker Hannifin Corporation
Precision Cooling Business Unit
Dale R. Thompson
phone [redacted]
[redacted]@parker.com

Vaporizable Dielectric Fluid Cooling for IGBT Power Semiconductors

David L. Saums, DS&A LLC, 100 High Street, Amesbury MA 01913 USA

Summary

An electrical drive utilizing a common dielectric fluid as the coolant in two-phase operation for cooling 1700V 450A Isolated Gate Bipolar Transistor semiconductor modules has been proposed and demonstrated as a proof-of-concept system. While water as a coolant is very common for such drive systems, a variety of liquids are used in commercial, industrial, aerospace, and military electronics systems. Use of water as a coolant is often regarded as the most prevalent fluid for commercial and industrial electrical drives. The use of alternative coolants is often determined by existing industry practices, component availability, and knowledge base for proven approaches. Use of water or deionized water may also require additives for biological control and antifreeze, colorants, and other inhibitors. The use of water may also require, variously, particle filters, deionization filters, and similar hardware components.

The consideration of alternative liquid coolants is driven by system requirements. System requirements impact several aspects of system design, including operating pressures, coolant heat capacity (including any required additives), safety, electrical hazard prevention, need for additives, and maintenance requirements.

An alternative cooling technology is the use of a dielectric liquid in a low-flow rate, pumped cooling system utilizing two-phase cooling (without the use of refrigeration), liquid cold plates, flow-through pumps, and a vapour condenser or heat exchanger. The use of such a system with a common vaporizable dielectric fluid will be described as a practical implementation in the power semiconductor market, with examples of individual applications in electronic systems. The vaporizable dielectric fluid is R-134a, a common refrigerant, selected for well-known properties and wide commercial availability at relatively low costs. The use of such refrigerants in pumped, low-flow systems required the development of pumps with and without flow-through cooling, specific to the fluid properties. Referred to as Variable Dielectric Fluid (VDF) cooling systems, these low-flow rate systems are now in use in commercial systems.

1 Introduction

Typical electric drive systems which require the use of liquid cooling rely on the use of water or deionized water as a coolant. Electrical drives for applications in aircraft applications frequently have utilized other liquid coolants, including dielectric fluids such as polyalphaolefin (PAO) and perfluorinated fluorocarbons (PFCs) from several manufacturers. Traction market electrical drives and other applications utilize newer dielectric fluids such as fluoroketones, also available from several manufacturers; some traction system electrical drives have utilized these dielectric fluids for direct immersion cooling of power semiconductor devices such as compression-pack assemblies and IGBT assemblies. Certain commercial and military systems use vapor-cycle compression with refrigerant fluids when sub-ambient temperatures must be maintained. For all electronic systems, liquid cooling is applied only when heat flux, total heat dissipation, system volume reduction, or other system design targets require greater heat transfer than air-cooling alone can provide.

Water cooling is a well-defined, well-understood thermal management technique that has been used for decades for power semiconductor and integrated circuit heat transfer. In addition, there are many components that are widely available from a large number of vendors in a variety of designs to meet system design requirements and cost targets. A typical single-phase water cooling system for a motor drive or traction drive consists of one or more liquid cold plates for mounting the heat sources and providing contact cooling to those sources, a pump, and a fan and heat exchanger located either within the system enclosure to eject the heated air locally; or a remote fan and heat exchanger located at some distance from the drive system. Tubing, hard plumbing, component quick-disconnects for ease of field maintenance, coolant filters, deionizing filter, and other components are selected to meet system design requirements. Water source and quality are specified to meet system operational and reliability requirements; in motor drives and electrical power transmission systems and other applications, water quality and particulate size limits may be tightly controlled.

The concept of a vaporizable dielectric fluid cooling system, which employs the heat of vaporization principle to significantly increase heat transfer within liquid cold plates for mounting power semiconductor heat sources, will be described. The primary components will be described and system operation and performance in an electrical drive will be compared to traditional air-cooling and single-phase water cooling performance.

2 Two-phase Pumped Dielectric Cooling

The use of a vaporizable dielectric liquid in a pumped system yields several significant advantages for thermal management of an electronic system:

- Extremely high efficiency of two-phase heat transport, utilizing heat of vaporization;
- Relatively low flow rates and low pressure drop;
- Highly-scalable system design with multiple isothermal liquid cold plates;
- Use of a dielectric fluid, eliminating concerns for mixed metals in a system;
- Many common refrigerants are relatively inert, important when used in contact with a wide variety of hose and fitting and seal materials;
- Inert, dielectric fluid such as R-134a may be used as the coolant for the pump windings, with pumps designed specifically for these applications;
- Addition of a small amount of a lubricant also enables the coolant to provide the lubrication for the pump head bearing system.
- System approach to design can be series or parallel cold plate operation, with no flow instability.

2.1 Principal Components

A two-phase pumped dielectric fluid cooling system has been developed which includes the following main components:

a. Liquid cold plates typically plumbed for series operation for multiple heat sources, with manifold and connectors. The cold plates may mount one IGBT per evaporator or multiple cold plates; as many as ten 1700V IGBT modules have been mounted on a single double-sided cold plate in one design.
b. One or more low-flow rate pump, designed for use with dielectric fluids. Pumps are of two basic designs: with and without flow-through cooling. Pumps developed for these systems with flow-through utilize the dielectric fluid as the pump windings and/or bearing coolant, with the fluid flowing across the windings. A small percentage of a common bearing lubricant may be added to the fluid (as is not uncommon in refrigeration system fluids for compressors), to provide required lubrication. Other pump designs may have a sealed pump head.
c. Condensers, for transfer of the heat load to the ambient air (or to a city water or chilled water supply), may be of a number of different designs. Fluid/air, fluid/fluid, or even fluid/refrigerated air or liquid may be used; condensers may be located remotely if required.
d. Ancillary system components may be installed to meet system design requirements; these components may include a filter/drier, flow meters and other control sensors, vapor/liquid separator, and an expansion tank. Figure 1 illustrates a layout with a single modular tray supporting three IGBT modules on individual liquid cold plates; the vapor/liquid separator shown is optional and not typically required.

2.1.1 Liquid Cold Plates

Use of an inert dielectric fluid as the system coolant allows the use of mixed metals in the system. A variety of designs and manufacturing methods for liquid cold plates may be used. Relatively high thermal performance can be achieved without the use of microchannel cold plates, reducing or eliminating concern for channel blockage due to bubble formation.

Use of simple, stamped convoluted fin pack inserts to create internal fin structures is a common technique used widely for water-cooling systems, although most commonly with vacuum brazed assembly. Oven brazing and joining of mixed metals for cold plate fabrication is possible with dielectric fluids, as there is no concern for galvanic action; in-line oven brazing is a cost reduction for cold plate manufacturing.

Existing liquid cold plates designed previously for water cooling systems may require modification of internal manifolding for use in a VDF system, to allow optimization for fluid behaviour in both liquid and vapour phases. Internal construction of cold plates, sizing of fluid channels, manifold design, and bubble formation in single- and two-phase cooling systems has been studied in wide number of academic institutions for a variety of coolants.

Performance data for mesoscale cold plates of the types used in these systems, manufactured with copper convoluted fin packs inserted into coolant channels in either copper or brass cold plate bodies, with oven-brazed top surfaces, are available for reference. [1]

2.1.2 Pump

Cooling systems which employ a dielectric fluid for electronics systems cooling have not been common in part because of the lack of commercially-available pumps. The lack of this critical component has prevented commercialization of such systems. This lack has been met by the recent development of dielectric fluid pumps by Parker Hannifin Corporation for integration into the first commercial ized VDF systems that are being manufactured and shipped by Parker Hannifin for electrical drives and other power semiconductor system applications. [2]

Pumped systems of this type operate at relatively low fluid flow rates. A system pressure drop of 1.7bar and fluid flow rate of 87LPH is typical, for example for a 3kW heat load in an inverter. In system design, the pump(s) are typically located at the lowest point on the system. An additional pump may be specified, as with any liquid cooling system, to provide redundant back-up.

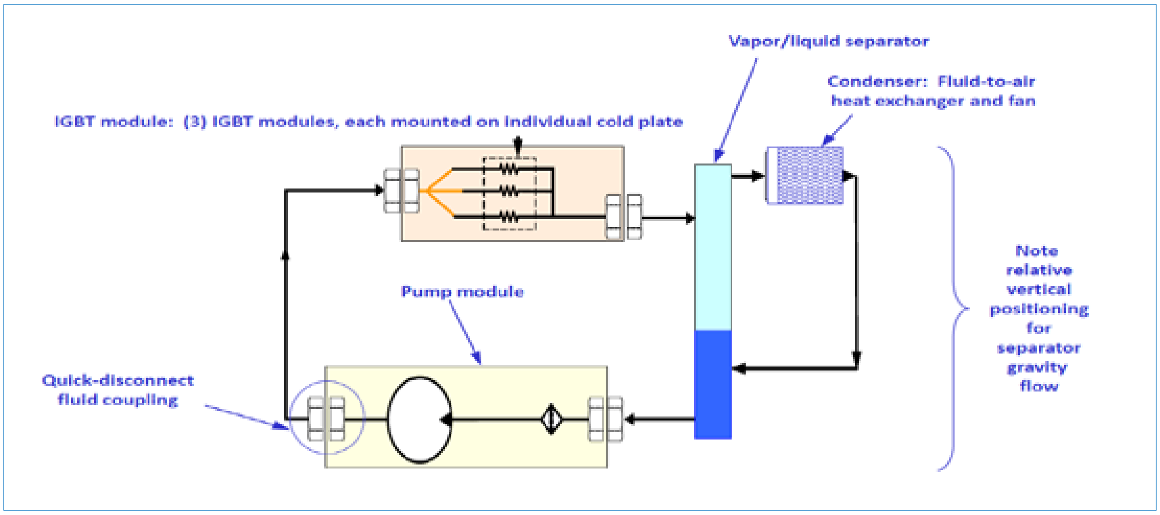


Figure 1 Components of a VDF system.

An important criterion for proper system design is that the fluid be 100% liquid upon return to the pump inlet, to eliminate potential for cavitation within the pump.

Pumps developed for use with vaporizable dielectric fluid cooling systems are derived from existing, proven pump types such as gerotor pumps, used in automotive and aerospace applications for moving oils. Design goals have included maintaining a minimum number of rotating components, the use of flow-through coolant over motor windings for motor cooling, and a minimum pump life (L_{10}) of 50,000 operating hours (3.4bar, 55°C inlet).

2.1.3 Condensers

Condensers used in a VDF system can be of a number of types; many designs are available from commercial sources for liquid cooling systems. For stationary electrical drives, the principal types are liquid-to-air (tube and fin) designs where the heat load is to be dumped to ambi ent air, either within a structure or outdoors; and liquid-to-liquid, if chilled water or city water is available for heat transport. Use of an inert dielectric fluid allows the system designer to use condensers with aluminium and/or copper internal construction and soldered or brazed joints.

Chillers, cooling towers, and a variety of liquid-to-air and liquid-to-liquid heat exchanger designs for water-based systems are applicable to dielectric fluid cooling. The condenser (heat exchanger) provides the mechanism for condensation of the vapor, returning the dielectric fluid in liquid phase to the pump. An optional system component is a vapour/liquid separator (not required in most commercial system designs completed to date).

2.1.4 Fluid Connectors and Tubing

Use of a modular design concept at the system level, with a reinforced sheet metal support tray for one or more cold plates and IGBTs; for a capacitor tray; and for a pump module with one or more pumps, supports creation of standardized modules.

Modules can be equipped with quick-disconnect fluid connectors to simplify field maintenance and replacement of system components. Many standard quick disconnects are available for a wide variety of fluids; as with other components, the use of an inert dielectric fluid as the coolant eliminates concerns for chemical degradation of connector sealing and gasketing materials.

As R-134a and many related refrigerants have been used worldwide for many years, there are a significant number of types of tubing materials available for use in dielectric fluid cooling systems. Use of hard-plumbed copper tubing and a variety of types of thermoplastic hosing (developed for automotive and other refrigeration applications) with high heat and ozone resistance are adaptable to use in a pumped R-134a system.

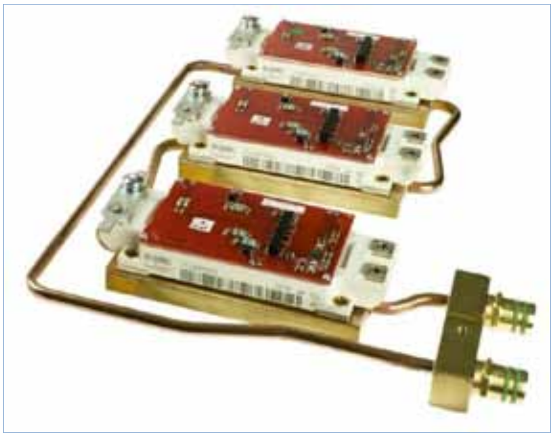


Figure 2 VDF Cooling system modular cold plate assembly and quick-disconnect couplings (sheet metal tray not shown for clarity).

2.2 Dielectric Coolants

While the heat capacity of water is recognized to be the highest of commonly-available fluids for electronics cooling, additives such as ethylene glycol will significantly reduce overall coolant heat capacity when used in a high mixture percentage. Frostproofing to -40°C, as an example, requires a concentration of 52% glycol.

Coolant (1 gram)	***Coolant Temperature Increase***	***Flow Rate Required to Dissipate 1kW***
Water	5°C (9.0°F)	174 l/hr. (46 gal./hr.)
R-134a (40°C)	(Isothermal at 40°C*)	21 l/hr. (5.5 gal./hr.)

** Note: Dependent upon system pressure.*

Figure 3 Comparison of flow rate required to dissipate 1kW of power. Relative performance is shown for water and R-134a refrigerant as coolants.

A refrigerant such as R-134a (ubiquitous for automotive air conditioning systems and consumer appliances) is a well-characterized coolant that is relatively inexpensive and widely available worldwide at low cost. R-134a is compatible with many types of seals, gaskets, hoses, and other components and materials. A refrigerant such as R-134a is non-flammable and non-toxic in reasonable quantities and, in the event of a leak, dissipates without causing an electrical short or any health risk to operators or maintenance personnel.

Global warming concerns for refrigerants have led to the development of newer chemistries. An example is HFO-1234yf, with a global warming potential rating (value of 4) that is below European Union requirements. These newer refrigerants are well-documented for automotive air conditioning applications and can be used without alteration in a pumped VDF cooling system. Continued testing and evaluation of HFO-1234yf is underway with major manufacturers. [3, 4]

3 Two-phase System Operation

Engineering for a two-phase pumped dielectric fluid cooling system is not trivial, although the componentry appears very similar to a single-phase water system. A major advantage of two-phase operation is the reduction of physical size of components and the volume of fluid required. The lower flow rates of these systems reduce the size of the pump, reservoir, tubing diameters, and power supply.

A pumped system depends in part on gravity flow, to return condensed vapour as liquid to the pump. The pump maintains a set pressure within the system, and system fluid temperature may be set by adjusting the system operating pressure. A higher pressure will increase the saturation temperature of the refrigerant, enabling a higher junction temperature for devices and either a smaller condenser volume or a lower airflow across the condenser. This ability to select an operating pressure setpoint for the system is an important feature of system operation. Note that while all of the discussion herein refers to the use of R-134a as the fluid, other refrigerants that have similar chemistries and different operating temperature ranges, for example, can be used.

Systems as designed are intended to be shipped for installation within an OEM drive system as either a complete, sealed system or in kit form. If shipped as a sealed system, there is no need for set-up with addition of the fluid and there is no need for draining of the fluid prior to air shipment, as refrigerants tolerate sub-freezing temperatures. There is no need for a make-up liquid maintenance process, when quick-disconnect (dry break) couplings are used in system design.

Key performance attributes of these systems include:

- Fluids such as R-134a are stable and inert.
- The system is self-optimizing.
- The system design point is optimized to a known system heat load as the design maximum; a safety margin is included to eliminate dry-out potential.

- Two-phase operation requires moderate vapor pressures, with these critical system features:
    - As device operating heat loads and heat fluxes rise, boiling rate increases within the device cold plates;
    - Near-instantaneous transition of system operating pressure increases or decreases rate of vaporization as required.
- R-134a, HFO-1234yf, and other refrigerants offer excellent relative heat capacity for electronics heat transfer, as compared to deionized water and ethylene glycol/water mixtures.
- A relative rule of thumb for thermal performance capability is that, for 1kW devices loads, mesochannel cold plate designs will remove up to heat fluxes approaching $1kW/cm^2$.
- System operation with mixed metals for components will not result in galvanic action.
- Low flow rates reduce possibility of cavitation.
- System is designed for 80% liquid/vapour quality, to ensure safety margin at design point for full liquid return to pump inlet.
- Low pump parasitic power consumption with low system fluid flow rate.

An enthalpy chart, traditionally used in the refrigeration industry to characterize the liquid/vapour performance for vapour cycle compression systems, is shown in Figure 4, below.

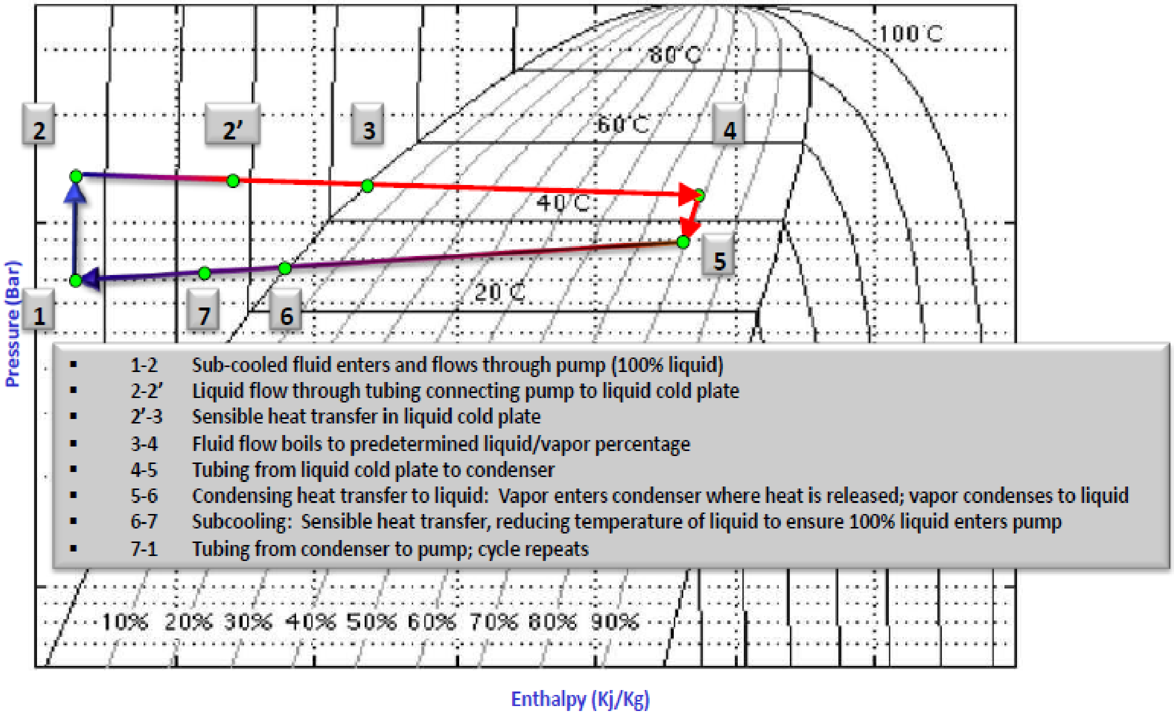
3.1 Case Study and Thermal Performance

A case study for an electrical drive has been developed with comparative test data for air-, water-, and pumped two-phase dielectric cooling systems in the same enclosures and loads. [1]

A production 750kW variable speed AC drive manufactured with an air-cooling system was packaged in three standard cabinets. A total of nine standard Infineon EconoDUAL™ 1700V, 450A IGBT modules, mounted individually on traditional air-cooled extruded heat sinks in three modular trays of three IGBTs per tray, were tested under two load conditions:

- 100% steady-state load
- 220% overload state for 10 seconds

The existing air-cooled production design required 255 m^3/hr. (150CFM) air flow and air-cooled heat sinks operating at 40°C. A second drive was assembled with a traditional water-cooling system, with a water flow rate of 436 l/hr. per cold plate, with cold plates operating in parallel at a total 1362 l/hr., maximum air temperature of 40°C, and maximum temperature rise in the heat exchanger of 10°C. The same system enclosures and modular IGBT mounting concept was utilized with a VDF system, with all-copper mesoscale liquid cold plates and pumped R-134a as the coolant. Five cooling solutions were compared; for the



.**Figure 4**. VDF system operating points.

same 750kW drive system with identical 1700V (blocking voltage) IGBT modules, a comparative evaluation of total power dissipated per device showed incremental additional heat removal capacity as shown in Figure 5.

Cooling Case	Thermal Solution	Module Loss@120°C Steady State (W)
A	Air cooled aluminum extruded heat sink	600
B	Water-cooled extruded aluminium cold plate	736
C	Water-cooled aluminium cold plate with copper cooling circuit aligned to die locations	1070
D	Water-cooled vacuum-brazed high-performance aluminum cold plate	1040
E1	VDF pumped R-134a convoluted copper cold plate	1461

Figure 5 Comparative test data for five cooling methods for 750kW AC drive.

Fluid flow rates for each tested cooling system in the case study are shown in Figure 6, below, which are useful to illustrate the significant reduction achieved with the pumped dielectric two-phase system.

Cooling Case	Thermal Solution	Fluid Flow Rate per Cold Plate LPH (GPH)
A	Air cooled aluminum extruded heat sink	N/A
B	Water-cooled extruded aluminium cold plate	454.2 (120.0)
C	Water-cooled aluminium cold plate with copper cooling circuit aligned to die locations	454.2 (120.0)
D	Water-cooled vacuum-brazed high-performance aluminum cold plate	454.2 (120.0)
E1	VDF pumped R-134a convoluted copper cold plate	90.6 (24.0)

Figure 6 Comparative fluid flow rate per liquid cold plate, for each cooling system tested.

4 Applications

Demonstrator and production applications for this concept include IGBT-based electrical drives for both stationary and mobile applications. These applications include:

- Variable speed AC drives
- 1MW uninterruptible power supply
- Power LED light engine for projections systems
- Industrial metal heat treating systems
- Magnetics
- Naval shipboard power sources
- Military vehicle hybrid electric vehicle power-train inverters

A demonstrator system for laboratory testing has also been designed, assembled with sensors and flowmeters and a complete data acquisition system, used for testing of newly-developed pumps and other components and for furthe development of these systems.

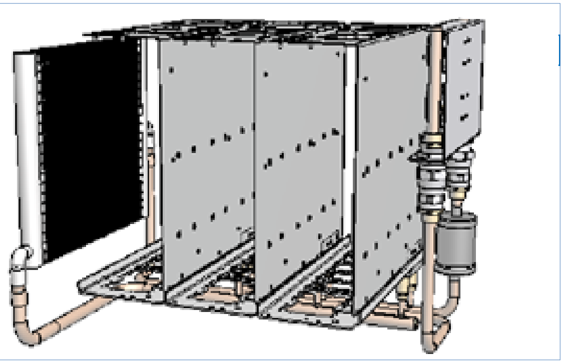


Figure 7. Modular VDF cooling system for hybrid vehicle powertrain inverter.

Figure 8. Modular VDF cooling system for hybrid vehicle powertrain inverter

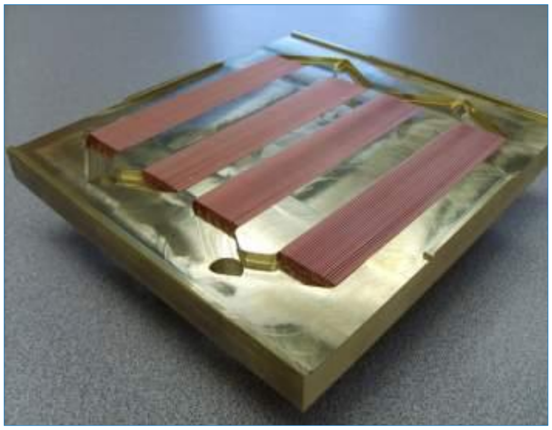


Figure 9. VDF cold plate, illustrating fluid manifolding and flow path through copper convoluted fin packs within a brass cold plate body (prior to final cover plate assembly and brazing). Cold plate is designed for 140mm x 130mm IGBT module mounting for vehichle HEV powertrain inverter cooling.

These vaporizable dielectric fluid systems and the related pumps developed for use in these systems are intended to be designed as a complete packaged cooling system. Pump development and system concepts are subject to pending patent applications and granted international patents to Parker Hannifin Corporation.

5 Conclusion

Power semiconductors, a key technology for improving energy efficiency for many applications, dissipate significant amounts of energy as waste heat. Effective and efficient means of removing that waste heat include newly-developed cooling systems employing R-134a and similar refrigerants, which are inert dielectric fluids commonly available globally. Use of these fluids in pumped, two-phase systems has been described and comparative performance data illustrated for air-, water-, and VDF-cooled systems.

These systems have recently been developed and commercialized for industrial, commercial, and vehicle applications. Use of such high-efficiency two-phase liquid cooling systems provides improvements in space utilization by reducing needed physical volumes, allowing for more compact system designs, and improving efficiency of waste heat removal for higher overall system performance.

6 Literature

[1] Hannemann, R., Mackey, S.: Design and Performance of Meso-Scale Evaporative Cold Plates, Proceedings, Binghamton University/GE Global Research Electronics Packaging Symposium 2007, Niskayuna NY USA, 1 August, 2007.

[2] Saums, D., Levett, D., Howes, J.: Cooling of IGBT Modules with Vaporizable Dielectric Fluid (VDF), International Microelectronics and Packaging Society France, 3rd Advanced Technology Workshop on Thermal Management and Micropackaging, La Rochelle, France, 30-31January, 2008.

[3] Spatz, M., Minor, B.: HFO-1234yf: A Low GWP Refrigerant for MAC, Society of Automotive Engineers World Congress, Detroit, Michigan USA, 14-17 April 2008.

[4] Hill, W.: SAE CRP1234: Risk Assessment and Performance Evaluation of HFO-1234yf, VDA Winter Meeting, Saalfenden, Austria, 12 February 2008.

[5] EconoDUAL™ is a trademark of Infineon Technologies, Warstein, Germany.