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Cooling of an IGBT Drive System with Vaporizable Dielectric Fluid (VDF)

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Abstract

The use of a vaporizable dielectric fluid is proposed and demonstrated in a proof-of-concept electrical drive system utilizing medium-range 1200VAC 450A IGBT devices. Comparative empirical data is shown for a drive system utilizing production components for a traditional air-cooled extruded aluminum heat sink thermal solution for each IGBT module, versus several water-cooled liquid cold plate solutions and a single-cabinet 750kW, 1,000-horsepower drive system utilizing low-flow, pumped liquid multiphase cooling. Positive and negative attributes of each thermal solution are described.

Keywords

Liquid cooling, pumped liquid multiphase, two-phase, pumped refrigerant, dielectric, vaporizable fluid, phase-change, condensing, industrial drive system, IGBT, alternative electronic cooling fluids.

Nomenclature

Δ	Change
HP	Horsepower
kW	Kilowatt
P	Pressure [Pa]
Θ	Theta, Thermal Resistance
Q	Power [W]

Terms and Acronyms:

HFC	Hydrofluorocarbon
IGBT	Isolated Gate Bipolar Transistor
LCP	Liquid Cold Plate
PLMC	Pumped Liquid Multiphase Cooling
R-134A	Refrigerant, HFC
VDF	Vaporizable Dielectric Liquid

1. Introduction

Traditional air-cooled aluminum extruded heat sinks are a well-defined, well-understood, and relatively inexpensive thermal management solution for medium- and high-voltage IGBT power semiconductor devices packaged in brick-style standard module formats. However, use of strictly air-cooled thermal management techniques for higher-power dissipation modules results in substantial physical volume required to handle large amounts of heat dissipated. The physical volume required and the costs for required fans, heat sinks, electrical bus bars to accommodate required spacing, cabinetry, and other factors may be reduced by utilizing more efficient cooling media, such as water. Water cooling is also a well-defined, well-understood thermal management scheme used for such systems in industrial applications. There are many designs and vendors available to the system design engineer for both air-cooled and water-cooled systems.

The use of a vaporizable dielectric liquid such as R-134A, a hydrofluorocarbon fluid that is ubiquitous in refrigeration systems for automobiles and many types of commercial and industrial applications, has been proposed as a fluid for thermal management of computing systems for individual processors dissipating up to 400W each, arrayed in a typical enterprise server system.[1] The same thermal management concept has been analyzed more recently for telcom equipment, examining the potential for total volume of space reduction as compared to traditional forced air cooling, for systems with components which are quite similar to those in an enterprise server.[2]

The use of a pumped two-phase system using a refrigerant, without compressor or compression cycle, has also been proposed for cooling power semiconductor devices.[3] This development project is described as a practical implementation of a pumped, low-flow two-phase liquid cooling system for cooling IGBT modules within an electrical drive system for industrial and power generation applications, with comparisons to the cost, performance, and volume reductions achieved and the net capacity increase available in the same configurations as the air- and water-cooled cabinets.

This is the first practical implementation of this system concept described in a proof-of-concept system intended to replace air- and water-cooled comparable drive systems in production for industrial use.

Key components of a vaporizable dielectric fluid cooling system are: liquid cold plates (sized appropriately for the particular components to be cooled and the VDF fluid to be used) in parallel or series, low-flow rate pump, condenser, and the VDF fluid selected. An air-cooled heat exchanger or one of several various types of fluid-to-liquid heat exchanger may be placed remotely from the cooled devices. Ancillary additional components may include a drier, quick-disconnect fittings for cold plates or in a modularized subsystem format, and pressure gauge. Distributors are used to properly provide fluid flow to cold plates; these are commonly-found components in the refrigeration industry.

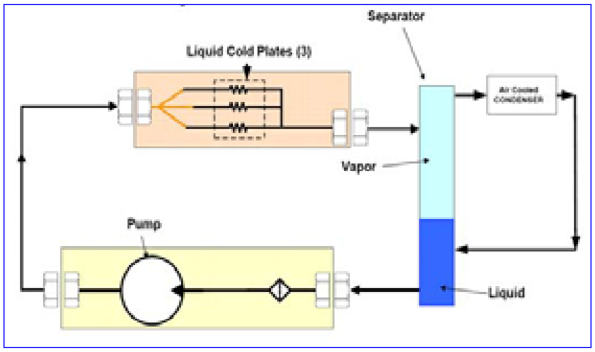

Figure 1: Vapor Dielectric Fluid (VDF) Cooling Loop.

A significant point of interest for comparison of any water-based liquid cooling system to the use of a vaporizable dielectric fluid in a two-phase system is the reduction in flow rate. A comparison may be drawn as follows:

Coolant (1 gram)	Energy Required	Coolant Temperature Increase	Flow Rate Required to Dissipate 1kW
Water	4.2J (0.00398 BTU)	5°C (1.8°F)	2.9 l/min. (46 gal./hr.)
R-134A (40°C)	151J (01243 BTU)	(Temperature at phase change*)	0.35 l/min. (5.8 gal./hr.

Note: * Dependent upon system pressure.

Table 1: Comparison of Flow Rate Required to Dissipate 1kW of Power.

The primary purpose of this calculation is to demonstrate the lower flow rate required for a vaporizable system in comparison to water. A lower fluid flow rate equates to design requirements enabling use of a smaller pump, smaller power supply, smaller reservoir, and smaller tube diameters throughout the cooling system. These are cost reductions for these components as compared to those required for a water system providing an equivalent heat dissipation task.

2. VDF Cooling System Design Characteristics

An important characteristic of a VDF cooling system is that the pressure and temperature are allowed to "float" relative to ambient conditions. The system is designed for a maximum power load at maximum anticipated ambient conditions; system pressure and fluid temperature follow known physical properties of such fluids. For a given system pressure, the resultant fluid temperature may be found from a reference chart of properties.

The system design engineer may set the refrigerant saturation temperature by adjusting the system operating pressure. This has a principal benefit for thermal management and system component design and cost:

- Setting a higher system operating pressure will increase the system fluid saturation temperature;
- A higher fluid saturation temperature will enable a higher junction temperature (within the limits of the device to be cooled);
- Higher junction temperature will enable use of a smaller condenser and/or lower airflow for an air-cooled system heat exchanger.

A very important note for the consideration of a VDF cooling system for electronics equipment is that the system does not use or require a compression cycle and there is no compressor used as a result

Use of a pumped vaporizable fluid without compression limits the ability of the overall system in one key aspect: the VDF cooling system cannot lower fluid temperatures below ambient temperatures. The minimum fluid temperature will be the heat exchanger medium temperature, reflecting whatever system operating pressure has been selected for an expected maximum system ambient temperature design point.

The use of refrigerant or other vaporizable dielectric fluids in place of water as a coolant for electronic systems will allow use of the equipment in outdoor ambient temperature extremes which are lower than, without the addition of ethylene glycol and other additives.

These systems also can be considered to be refrigerant-agnostic, wherein a number of alternative refrigerants and other vaporizable dielectric fluids exist which demonstrate differing known physical properties that may be useful for varied equipment design requirements. Certain refrigerants, for example, are useful where higher system operating temperature requirements are required or expected (due either to device operating characteristics or anticipation of raised ambient temperatures).

No biological agent preventative additives need be considered; R-134A and other common fluids are not toxic and should be selected from non-flammable chemistries.

No leak of a dielectric fluid will create a catastrophic electrical failure of the electronic system components.

Other key points of the VDF cooling loop concept that affect system design are:

- System is gravity fed;
- Pump must be located below liquid cold plates in the same cooling loop;
- Heat exchanger must be located above cold plates;
- Heat exchanger may be fluid-to-air (traditional tube-and-fin style) or fluid-to-water (shell-and-tube for external chilled water or cooling tower).

3. 750kW/1000HP Drive System Design

A complete three-phase electrical drive system was developed for industrial and commercial applications, incorporating different thermal solutions for the primary heat sources, the individual IGBT (Isolated Gate Bipolar Transistor) semiconductor devices. Each cooling system configuration was tested utilizing the same IGBT module type, a dual 1700V 450A module packaged in an industry-standard package design referred to as the EconoDUAL™ design. A similar package design is common to several semiconductor manufacturers. The module footprint measures approximately 122m in length and 62mm in width; these modules have a large, flat nickel-plated copper baseplate of standard thickness as the primary heat-spreading component for the module itself. Typically, six large IGBT die and six smaller diode die are arrayed in format consisting of two IGBT die and two diode die each, soldered onto a direct bond copper (DBC) substrate containing a ceramic dielectric layer and an additional layer of copper. DBC substrates are soldered to the nickel-plated copper baseplate. These are medium-voltage modules for many industrial electrical drive system applications, including turbines, marine drive systems, elevators, and motor drives.

An example of the power semiconductor module and packaging, as used in this system, is shown in Figure 2. The cover has been removed in this photograph.

Figure 2: IGBT power semiconductor module (1200V 450A)

Three IGBT modules are connected in one electrical and mechanical assembly and may be configured in one of two ways:

- Three-phase bridge;
- Single dual switch, operating in parallel.

4. System and Module Operating Loads and Testing

Functional modules for system testing were obtained a production modules from the semiconductor manufacturer One change was made for testing purposes by th manufacturer: an internal protective gel was not applied ove the die and DBC arrays and a black paint was applied fo improved emissivity, for measurement of die temperature with an infrared camera.

All die operating temperatures within each IGBT modul were measured with a thermal camera, with power applie under several conditions to simulate drive system loads.

Maximum module load was measured for each type o cooling solution employed in the prototype assembly, t produce an IGBT junction temperature of 120°C.

Two operating test conditions were selected based o industry practice and typical load cycles experienced in heav traction applications, common to these and higher voltag IGBTs:

A. 100% steady-state load;
B. Load condition with 220% overload capabilit for a 10-second duration.

Overload capability is important in routine operation o power semiconductors utilized in industrial motor driv systems, traction drive systems, and other commonly occurring situations. Ability of the thermal managemen system to handle expected overload conditions for the powe system is important to avoid catastrophic failure.

5. Thermal Solution Description and Test Cases

Five basic thermal solution concepts were tested fo operation in this drive system. These concepts include current production air-cooled components and newly developed cold plates. The individual thermal solutions ar identified by case as shown with a brief description in Tabl 2.

An example of the complete single-phase assembly wit three IGBT modules is shown in Figure 3, with one (of thre in parallel) Case C liquid cold plate visible.

Figure 3: Three-module assembly, bus capacitors at top. (Liquid cold plate illustrated is one of three, per Case C.)

Case	Thermal Solution	General Description
A	Air-cooled extruded aluminum heat sink, common geometry.	Current production system design (14:1 fin ratio).
B	Water-cooled standard extruded aluminum liquid cold plate	Press-fit continuous copper tubing (back side, no epoxy).
C	Water-cooled aluminum liquid cold plate, custom; tubing circuit aligned to die locations.	Machined surface, continuous copper D-shaped tubing, epoxy-bonded into device mounting surface of plate.
D	Water-cooled aluminum liquid cold plate, custom design.	Aluminum offset convoluted fin brazed into machined cavity; machined mounting surface.
E1	VDF-cooled copper cold plate, custom design (450A devices).	Copper straight fin convoluted fin brazed into machined cavity; machined mounting surface.
E2	VDF-cooled copper cold plate, custom design (225A devices).	Copper straight fin convoluted fin brazed into machined cavity; machined mounting surface.

Table 2: Thermal Solution Description by Case

Operation of the thermal solution described in each case, above, assumed typical ambient operating conditions for an IGBT drive system of this type. Drives may be used in high ambient temperature conditions; for the purposes of testing, a vertical cabinet orientation without excessive tilting from vertical was assumed. While not commonly considered for server and telcom equipment cabinets, the potential for some degree of movement for a drive system of this type employed in marine, offshore drilling, and similar applications is not uncommon.

Additional test conditions were assumed per Table 3, again assuming that typical operating conditions in an industrial application environment should be applied.

Case	Air Flow CFM	Fluid FlowRate Per Cold Plate LPM (GPM)	Fluid Flow Rate, Parallel, Total LPM (GPM)	Temp. Rise Heat Exchanger
A	150	N/A	N/A	N/A
B		7.57 (2.0)	22.71 (6.0)	10°C
C		7.57 (2.0)	22.71 (6.0)	10°C
D		7.57 (2.0)	22.71 (6.0)	10°C
E1		1.51 (0.4)	4.53 (1.2)	10°C
E2		1.51 (0.4)	4.53 (1.2)	10°C

Table 3: Test Operating Conditions by Case

The prototype VDF-cooled copper convoluted fin col plate used in Case E1 and Case E2 is shown in Figure 3.

Figure 3: VDF-cooled copper convoluted fin cold pla (Case E1, E2).

6. Test Results

7. Conclusions

Place conclusions here.

Acknowledgments

Place acknowledgments here, if needed.

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4.

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Additional topics:
Fluids

Dielectric strength, other characteristics of fluids