

Vaporizable Dielectric Fluid Cooling of IGBT Power Semiconductors

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Abstract—Liquid cooling system concepts for power semiconductors and other applications have traditionally focused on the use of a single-phase liquid, typically water modified with anti-freeze agents (ethylene or propylene glycol), corrosion inhibitors, and other additives; or the use of single-phase deionized water. Selection of such a common liquid coolant is driven by commonality requirements, the traditional knowledge and experience with water and water systems, and the perception of simplicity. A wide vendor base exists for components and various additives. The typical solution is a single-phase pumped loop system with sensible heat transport, high flow rates, and relatively large volumes of water and large component sizes. Use of other fluids has been investigated and, especially in military and aerospace applications, a small number of other fluids have become common to meet specialized requirements. Recently, the use of a vaporizable dielectric fluid (VDF) in a pumped liquid cooling system has been demonstrated and commercialized as a practical system-level thermal management solution for isolated gate bipolar transistors (IGBTs) in electrical drives and for commercial processors for computing systems. The use of this type of fluid and a two-phase cooling system concept for cooling semiconductor and other devices impacts several aspects of system design, including liquid coolant heat capacity, need for additives, safety, potential for volume reduction, and electrical hazard prevention. Advantages of a two-phase system using newly-developed liquid pumps and isothermal liquid cold plates are described; positive and negative aspects for certain applications are described. This system concept also offers advantages for developing hybrid and electric vehicle powertrain components and batteries.

Keywords: IGBT; vaporizable; dielectric; liquid cooling; heat of vaporization; pumped two-phase.

Acronyms and Terms:

FK	Fluoroketone
HFC	Hydrofluorocarbon
IGBT	Isolated gate bipolar transistor
LCP	Liquid cold plate
PAO	Polyalphaolefin
R-134a	Refrigerant (HFC)
HFO-1234yf	Refrigerant
VDF	Vaporizable Dielectric Fluid Cooling

I. INTRODUCTION

A cooling technology which uses a dielectric liquid in a pumped loop system with two-phase operation will be described. The use of a vaporizable fluid that is a dielectric is a critical aspect of the system design and important in considering a potential application. The fluid used is R-134a, a common refrigerant that is available globally from many suppliers for automotive, commercial, and consumer air conditioning systems. The demonstrated viability and life and reliability of air conditioning systems used in high-volume applications such as home air conditioners and refrigerators is well known. Low-flow rate, positive displacement pumps have been developed for use with these systems; vapor condensers are widely available from many suppliers; and a number of two-phase liquid cold plates have been developed. To meet concerns for reducing greenhouse gases and reducing the forecast global warming potential, new dielectric refrigerant fluids are expected to be available in these systems that will not require any system or component modifications. While this system concept has been commercialized in 2009 and is shipping for use in stationary electrical drives, there are a number of potential applications across the power semiconductor market where development work indicates that useful practical attributes and potential for cost reduction may exist, versus traditional industry practice with water-based cooling systems. While many applications are expected to continue to use water-based cooling, the availability of commercial VDF systems is a new and significant design choice available to the practicing thermal engineer. Comparative data and positive and negative attributes will be shown.

Development work for evaluation and implementation in a variety of electronic systems, including electric drives for powertrains for heavy military and commercial vehicles and railroad traction applications, utilizes many components and analyses developed for the initial system designs.

A. *Liquid Cooling of Electronic Systems*

Electronic system liquid cooling has been studied in innumerable academic investigations, both for single- and two-phase performance; is well understood, especially in single-phase operation; and has been implemented in a wide range of production electronic systems for decades. Practicality and cost requirements drive the use of natural convection or forced convection cooling with air wherever possible, in most electronic systems. Liquid cooling in many different forms will be considered only where required because of high heat fluxes, very high overall power dissipation requirements, or where other application-specific conditions exist (such as very high ambient temperatures, extreme restriction on physical volumes available for large air-cooled heat sinks, or where close control of temperature is critical to operation). While liquid cooling may sometimes be viewed in electronic systems by some as being an exotic solution, the technique is in wide use in selected segments of the electronics industry.

When liquid cooling solutions are required, water is a very useful and practical coolant for many low-cost applications. In high value or critical electronics systems such as medical instrumentation or semiconductor test equipment or enterprise computing systems, the specific water coolant utilized may in fact be a very carefully controlled coolant with specific requirements for pH level, particulate and contaminant limits, electrical resistivity, corrosion protection, and other qualities.[1] Many specialty pumps, condensers, liquid cold plates (LCPs), deionized filter cartridge systems, fittings and disconnects, and other components and additives have been developed to meet different requirements to enable the use of water.

B. *Selection of Liquid Coolant*

Single-phase water, deionized or not, has been the primary coolant utilized in industry. This is due to the high relative heat capacity of the basic fluid, wide availability, and number of components available for commercial applications.

Water used for power electronics and computing systems as a coolant may be one of several fluids: deionized water, mixtures of water and a selected glycol to control water behavior at temperature extremes, or another variant filtered and controlled to meet certain requirements. Requirements for purity, corrosively, and electrical resistivity for water and electrically-conductive liquids may be highly specific in certain electronic cooling systems. [1, 2]

Aerospace applications which require liquid cooling have used dielectric liquids such as 3M Company's family of Fluorinert™ liquids in the past, as well as polyalphaolefin (PAO). The current commercial dielectric liquids available for new system designs includes the 3M HFE and FK chemistries, as well as competing fluids from other suppliers, which meet environmental concern for zero or very low Greenhouse Gas (GHG) and Global Warming Potential (GWP) initiatives worldwide. These fluids are also used in semiconductor manufacturing equipment, test equipment, certain types of laboratory instruments, and immersion cooling applications. Recent new work has been documented with these fluids has been documented, in immersion cooling of IGBTs. [3]

Requirements for system operation, maintenance, and upgrade will influence which liquids may be used, the result of an engineering selection process by the system mechanical engineering team to meet performance and cost requirements and program objectives. In certain market segments and applications, a fluid may be dictated for a specific system platform, such as in military applications where field availability and logistics of supply may be critical, for maintenance purposes, or where electrical requirements prevail. An example may be the specification by an airframe manufacturer for the specific fluid to be used where multiple electronic systems must meet commonality requirements, both for fluid supply and for maintenance. These requirements are specific to each application type or market segment and frequently apply no matter whether the chosen fluid is deionized water, PAO, or some other fluid.

Selection of single- versus two-phase liquid system design is also a major design decision point. This selection is frequently primarily determined by source heat fluxes and design targets for maximum thermal performance. Extremely high heat fluxes in systems with serious volume constraints may dictate the use only of immersion cooling with boiling; a dielectric liquid is therefore a primary choice. While use of single-phase liquid cooling systems with a water coolant [either deionized water or water/glycol mixtures such as propylene glycol (referred to in practice as PEG), or ethylene glycol (WEG)] is the predominant liquid solution globally for electronics thermal management, other choices may be made. Deep engineering knowledge exists for water-based cooling at many OEM companies, universities, and research institutions, supported by a large and well-established component vendor base worldwide. Principal system components include a pump, heat exchanger, fans, one or multiple liquid cold plates, filters, expansion tank, flow meters and other control components, and a deionization unit (with field-replaceable deionization cartridge, for deionized water systems).

The automotive market has traditionally used a pressurized, closed water/ethylene glycol loop as the predominant liquid cooling solution for internal combustion engine (ICE) cooling. This same practice applies for the traction market globally, for diesel-electric and electric-drive passenger and freight locomotives, high-speed trainsets, and electric multiple unit and urban transit railcars in many forms. Implementation of hybrid electric vehicle (HEV), plug-in hybrid vehicle (PHEV) and electric vehicle powertrains has now added the need to cool temperature-sensitive power electronics to many vehicle platforms, both in the consumer automotive segments and in many other vehicle types. The use of the ICE cooling loop coolant for the power electronics drivetrain components is limited by the high temperature of the ICE coolant. This has led to the implementation of separate closed-loop liquid circuits operating at lower average temperatures.

Pumped vaporizable dielectric liquid systems where boiling is induced has not been generally available in electronic systems as a thermal design tool. There has been a large amount of research in two-phase cooling at universities and industry for many other types of applications, including large heat exchange and cooling systems for power plants and other non-electronics applications. In computing, IBM

Corporation's Liquid Encapsulated Module (LEM) was ground-breaking in the early 1970s (although not implemented in production systems). Much more recent research has led to the production implementation of both water cooling and refrigeration for large enterprise servers. [4]

C. Pumped Two-Phase Dielectric Fluid Solutions

Heat source heat fluxes have increased rapidly in some types of systems, leading to renewed investigation of two-phase systems. The development and use of two-phase systems which utilize a pump yields an important additional design choice. Note that there is no compressor, as this is not a vapor cycle refrigeration system. This solution, with newly-developed pumps that are critical to making this type of system functional and practical, may prove to be a paradigm shift in industry understanding of how liquid cooling may be applied. This approach is a step between single-phase liquid cooling and full vapor cycle compression refrigeration, appropriate for high heat flux devices where sub-ambient cooling is not required.

The primary objective for considering a two-phase liquid system is to harness the substantial increase in overall thermal performance obtained with boiling within each liquid cold plate. A typical rule of thumb is that the heat of vaporization principle will yield a two- to four-times increase in total heat transport capability.

Heat of vaporization is utilized in simple and effective heat pipe and vapor chamber designs used widely in electronic systems. Heat pipes and vapor chambers are useful components that can be easily applied to solving thermal problems. The total capacity of heat pipe and vapor chamber designs is significantly lower than that of a pumped two-phase system; the heat load cannot easily be transported large distances to a remote condenser; and each heat pipe or vapor chamber is typically applied only to the modest heat load of a single device.

Pumped VDF thermal management systems are self-optimizing. This is a critical distinction, as system performance is controlled by the heat load: as the power load increases, as switching increases and heat dissipation rises, the amount of boiling increases to withdraw the incremental heat load. As the power load decreases as switching work slows, the boiling rate decreases. Each such increase or decrease is a near-instantaneous change, providing a self-regulating and efficient feature. The pumped two-phase system adds the benefit of a pump to multiply the potential heat removal capability, as compared to the performance of a heat pipe.

D. Comparison of VDF Cooling to Refrigeration

Prior to the introduction of VDF cooling, the next step beyond single-phase liquid heat transfer is to traditional vapor cycle compression. The key differentiation for system performance between VDF and refrigeration is that VDF systems cannot obtain sub-ambient temperatures. Refrigeration provides an excellent, compact solution for high heat flux thermal management, but with added cost and complexity.

Limitations of traditional vapor cycle compression (VCC) systems are the lack of continuous duty small compressors with adequate reliability in continuous duty of 50,000 hours and the increased complexity in managing the evaporator temperature and head pressure. Some system designs may be limited by concerns for dew point and condensation in proximity to electronic circuits; high internal pressures and safety concerns; loss-of-coolant requirements (such as in military aerospace designs); or other considerations. No one concept or technique will be a universal solution.

An important feature of VDF cooling is the fact that an isothermal or near-isothermal cold plate mounting surface is achieved. To characterize this in general terms, a typical liquid cold plate for IGBT power semiconductor cooling may exhibit less than 1°C in temperature variation across a cold plate surface (e.g., 150-200mm in length) with multiple high heat source components mounted.

A further important feature is the elimination of thermal "stacking" wherein coolant temperature rises with each heat load at each cold plate when operated in series. The small change in pressure at each cold plate will result in a *reduction in temperature* of the fluid as energy is absorbed by the liquid-to-vapor transition within the cold plate. The system must be designed for a maximum heat load at a known maximum ambient temperature; pressure is used as a design set point for the system. The elimination of thermal stacking in series operation is contrary to the *increase* in temperature experienced within each LCP in a single-phase system. The size of the required condenser will also change as the system pressure and operating temperatures are adjusted.

Power densification and physical volume and weight reduction are additional objectives that can be achieved by implementing a VDF cooling solution. The physical volume required and costs for required fans and heat sinks for increased power dissipation, for air-cooled solutions; the electrical bus bars to accommodate required spacing; larger cabinets; and other factors may be reduced by utilizing more efficient cooling media, such as liquids. The heat of vaporization principal for a two-phase liquid system can be demonstrated to result in efficiencies that reduce physical volume and overall weight.

II. SYSTEM CONCEPTS AND THERMAL PERFORMANCE

A. Thermal Performance of Refrigerants as Coolants

VDF cooling systems have been investigated and developed for thermal management of computing systems with processors dissipating up to 400W each, in a large enterprise server system. [5, 6]

The fluid chosen, R-134a, is a commodity fluid that is ubiquitous in refrigeration systems for automobiles and commercial and industrial applications. Table 1 shows a thermal performance comparison for the physical properties of R-134a and water.

TABLE I. REFRIGERANTS AS LIQUID COOLANTS

Coolant (1 gram)	Coolant Temperature Increase	Flow Rate Required to Dissipate 1kW
Water	5°C (9.0°F)	2.9 l/min. (46 gal./hr.)
R-134a (40°C)	(Isothermal at 40°C*)	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:
Relative performance of water and R-134a refrigerant as a coolant.

Safety considerations are important in electrical system design and an important distinction for dielectric fluid systems is that a fluid leak will result only in vaporization of the fluid. For R-134a, the fluid vaporizes in contact with hot components without shorting electrical or electronic components and is non-toxic in reasonable quantities.

R-134a refrigerant is available from a large number of suppliers, low in cost, and well-characterized for many types of refrigeration applications. Many types of tubing, connectors, condensers, and manifolds have been used for

decades in refrigeration systems. Availability of system components adds design flexibility; offers potential cost savings from proven manufacturing processes; and incorporates proven reliability of quick disconnects and manifolds manufactured for commercial refrigeration systems.

B. Principal VDF System Components

Major components for a pumped VDF cooling system developed for cooling power semiconductor devices are shown in Figure 1. A proof-of-concept implementation within an electrical drive system for industrial and power generation applications has been completed and tested. Cost, cooling performance, and volume reductions achieved and the net system capacity increase have been documented. Practical implementation of this system concept, replacing air- and water-cooled electrical drives, has very recently entered production for industrial electrical drives. [7, 8] Other applications are being examined.

Main components of a two-phase dielectric fluid cooling system are:

- Liquid cold plate evaporators in parallel or series for one or multiple heat sources, with manifold and connectors;
- Low-flow rate pump(s) for dielectric fluids;
- Condenser (heat exchanger).
- Ancillary components, per system specifications.

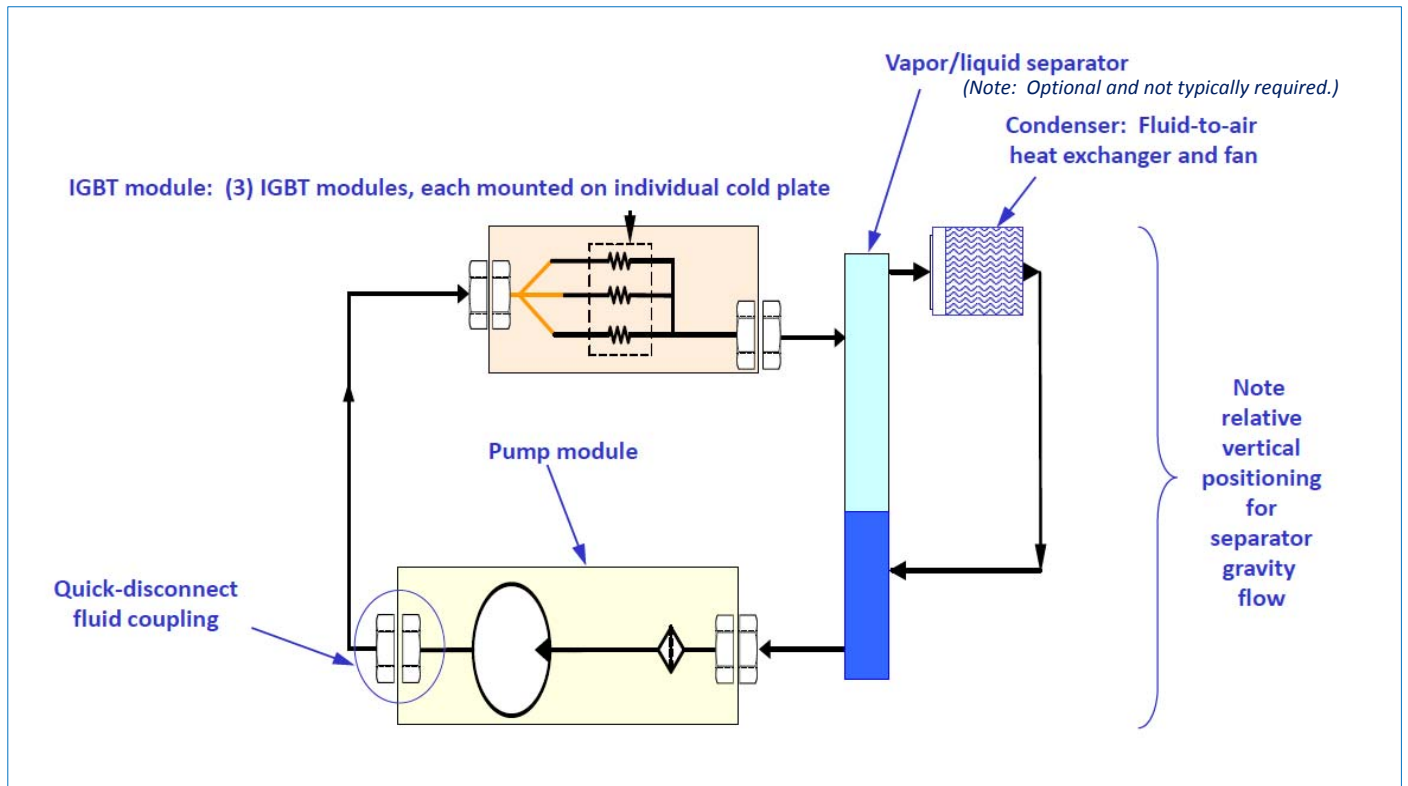


Figure 1: Components and relative positioning of VDF system components.

Examples of ancillary system components include: filter/drier, vapor liquid separator, flow meters, control sensors, or an expansion tank.

Condenser:

Virtually any type of existing condenser may be used. This may be either a fluid-to-air (tube and fin or similar) or fluid-to-liquid (shell and tube, plate fin), or a connection to a remote condenser or cooling tower.

Liquid-Vapor Separator:

The liquid-vapor separator is an optional component, used in certain system designs. If specified, the separator acts as a liquid accumulator, returning 100% liquid to the pump inlet and sending vapor to the condenser.

Liquid Cold Plates:

Liquid cold plates have been developed for use with the VDF cooling system and are inexpensive. Modification of existing LCPs designed for water or other fluid may require internal manifolding and channel spacing for use in a VDF system, reflecting the lower viscosity of R-134a as compared to water. Modification allows for optimization for fluid behavior in both liquid and vapor phases.

The isothermal condition of a liquid cold plate for a pumped two-phase dielectric system is an important feature; not only is the surface of the individual cold plate relatively isothermal, the same isothermal condition applies across arrays of cold plates in series and parallel. The isothermal (or near-isothermal) operation of cold plates in series eliminates concerns for "thermal stacking". In a typical water system, the first liquid cold plate in a series arrangement operates at the lowest temperature, with successively higher temperatures for each cold plate in the system as these succeeding cold plates are pre-heated by the hot liquid from the downstream devices.

This pre-heating does not occur with the VDF cooling system.

VDF cold plates arranged in series operate in a way such that only a portion of the liquid refrigerant evaporates from liquid to vapor in each cold plate. Therefore, if pressure drop across an individual cold plate is modest (typically, 2 PSI or less), each cold plate in series will have the same saturation temperature. The only property that changes is the vapor quality. The unevaporated liquid along with the vapor from the previous cold plate feeds the next cold plate where more evaporation takes place at essentially the same saturation temperature. Test results have shown that for three cold plates in series, each operating at 1kW dissipation (3 kW total), the temperature difference between the first cold plate and the last cold plate is less than 2°C.[5, 6, 7]

Pumps:

Specialized pumps have been developed for dielectric fluid cooling, critical to the operation of the system. Pumps of two types have been developed: (A) Gerotor pumps which utilize the dielectric fluid as the pump bearing and winding coolant, with the fluid flowing across the windings and in direct contact with the bearing system. In these designs, a small percentage

of a common bearing lubricant is added to the dielectric fluid, to provide the required bearing lubrication. (B) Pumps with a sealed pump head. Selection of the appropriate pump to match necessary flow rates and system operating pressure is critical to system design and reliability.

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.

Comparison of any water liquid cooling system to a pumped vaporizable dielectric fluid system can show a large reduction in flow rate in the VDF system. A comparison may be drawn as a calculation demonstrates (Table 1) the lower flow rate that is required for a vaporizable system in comparison to water. The value of lower fluid flow rate for system design is: use of a smaller pump, smaller reservoir, smaller volume of fluid, and smaller tube diameters and other components throughout the cooling system. This is a potential cost reduction for components as compared to those required for a water system providing an equal heat dissipation task.

Smaller component sizes and volume of fluid result in reduced system weight and overall physical volume, important in many areas for power semiconductor applications. Reduced coolant system size may mean reductions can be achieved in other mechanical system components, including sheet metal and other enclosure components.

C. VDF Cooling System Design Characteristics

Ambient temperature changes with a two-phase system can be compensated for in system operation, where the pressure and temperature are allowed to "float" relative to ambient conditions. Normal system design procedures are to design for a maximum system power load, at maximum anticipated ambient conditions; system pressure and fluid temperature follow known physical properties of the fluids. For a given system pressure, the resultant fluid temperature may be found from a reference chart of fluid properties.

An overall system design target is to select a vapor quality maximum value, at the exit of the last liquid cold plate in series; a typical value is 70% vapor quality at exit. [Vapor quality refers to the ratio of vapor to total fluid (70% of the total fluid is vapor in this example.)] Setting a maximum vapor quality value is an important system safety requirement, to prevent so-called "dry-out" from occurring within the liquid cold plate.

The self-optimizing characteristic of these systems has been identified previously. This is an important attribute for system control mechanisms.

A critical system design requirement is to design for 100% liquid return to the pump inlet, to maximize pump performance operating life. This target is met by specifying a minimum condenser capacity for the system, maintaining a proper gravity return to the pump, and placement of components to ensure proper system operation.

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

- System fluid saturation temperature can be increased by setting a higher system operating pressure;
- A higher fluid saturation temperature will enable a higher junction temperature (within the limits of the device to be cooled);
- Setting a higher operating temperature (where feasible for devices) adds another attribute for system design: either a smaller condenser can be used, further reducing system size, or a lower airflow can be set, reducing acoustic noise and power consumption or the ability to dissipate in high ambient conditions.

Other key points of the VDF cooling loop concept are:

- System is gravity fed;
- Pump should 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).
- Liquid cooling is employed for the critical high heat sources in typical system design with air cooling for parasitic

heating in other areas, such as capacitor trays; these decisions are design-specific.

D. Maximum Coolant Operating Temperatures

A two-phase pumped system is a pressurized system which does not contain a compressor. There is no opportunity in a VDF system to operate at sub-ambient temperatures. The minimum fluid temperature will be the heat exchanger medium temperature. This will reflect the system operating pressure selected by the system design engineer for an expected maximum system ambient temperature design point.

VDF cooling systems are considered to be “refrigerant-agnostic” (meaning that any appropriate fluid can be used which meets requirements for a vaporizable dielectric with reasonable characteristics). A potential new refrigerant which the industry expects will enter production before 2011 (to meet environment guidelines) is HFO-1234yf, intended to become a standard refrigerant for use wherever R-134a is used. For systems with unusual operating requirements, such as very high system operating temperatures, other refrigerants are already in use that meet this requirement. Certain refrigerants have also been approved by government agencies and military services in unusual cases, such as the approval of R-236fa by the US Navy for very specific applications.

Certain types of power electronic systems must be designed for unusually high temperature operating conditions; an

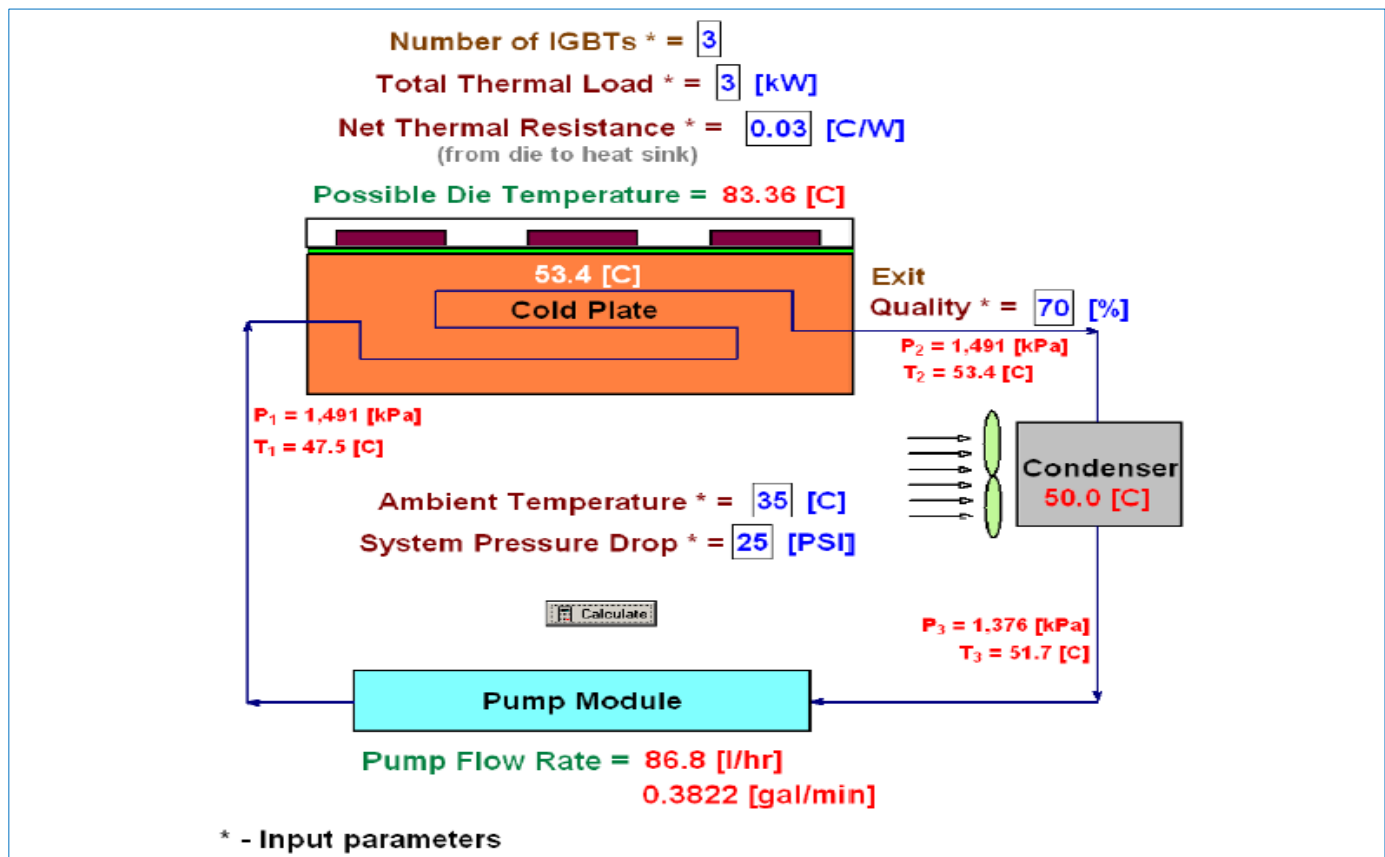


Figure 2. Example of system-level VDF operation model for 3kW heat load at cold plate and given ambient temperature, showing calculated liquid flow rate and die and cold plate temperatures. Values shown are typical of an example of inverter IGBT cooling requirements in an outdoor environment.

example is the pulsed operation of a medical laser system. When water is used in such systems, concern for algae and other biological growth may require use of algacides and biocides. No biological control agent or other control additive is needed for R-134a systems.

E. Minimum Coolant Operating Temperatures

No ethylene glycol or other antifreezing agent is required for R-134a systems, even for subzero conditions. The requirement for thermal derating for antifreeze and water mixtures is eliminated. Derating can be significant degradation of a glycol/water system thermal performance calculation, as derating values rise to 35-55% for the most challenging external temperatures. A typical example in the traction industry for IGBT cooling systems is a cold-start temperature of -55°C for railroad locomotives supplied to Russia; the derating applied for water mixtures may be greater than 45%.

III. PROTOTYPE 750kW/1000HP DRIVE SYSTEM DESIGN

A. System Design

A VDF cooling system was designed for a proof-of-concept test program for a stationary industrial electrical drive. Test data for VDF and water cooling systems are described, with a description of the complete three-phase electrical drive and the associated air-, water-, and VDF cooling solutions used.

Each cooling system configuration was tested utilizing the same IGBT module type, a dual 1700VAC 450A module

in an industry-standard package design referred to as the EconoDUAL™ design. [9] This IGBT package footprint is common to several semiconductor manufacturers. This module has a large, flat nickel-plated copper base plate (122mm x 62mm) of standard thickness as the primary heat-spreading component for the module.

Six large IGBT die and six smaller diode die are arrayed in a format within the EconoDUAL IGBT module that consist of a pair of two IGBT die arrayed with two diode die each, soldered onto a direct bond copper (DBC) substrate containing a ceramic dielectric layer and one or more copper layers. DBC substrates are soldered to the nickel-plated copper base plate. These are standard medium-voltage modules for industrial electrical drive system applications, including turbines, marine drive systems, elevators, and motor drives.

Three IGBT modules are connected in one electrical and mechanical assembly (as shown in Figure 3) and may be configured in one of two ways:

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

B. Module and System Operating Loads and Testing

Functional IGBT modules for system testing were obtained as production modules from the semiconductor manufacturer. One change was made for testing purposes by the manufacturer: an internal protective gel was not applied over the die and DBC arrays and a black paint was applied for improved emissivity, for measurement of die temperatures with

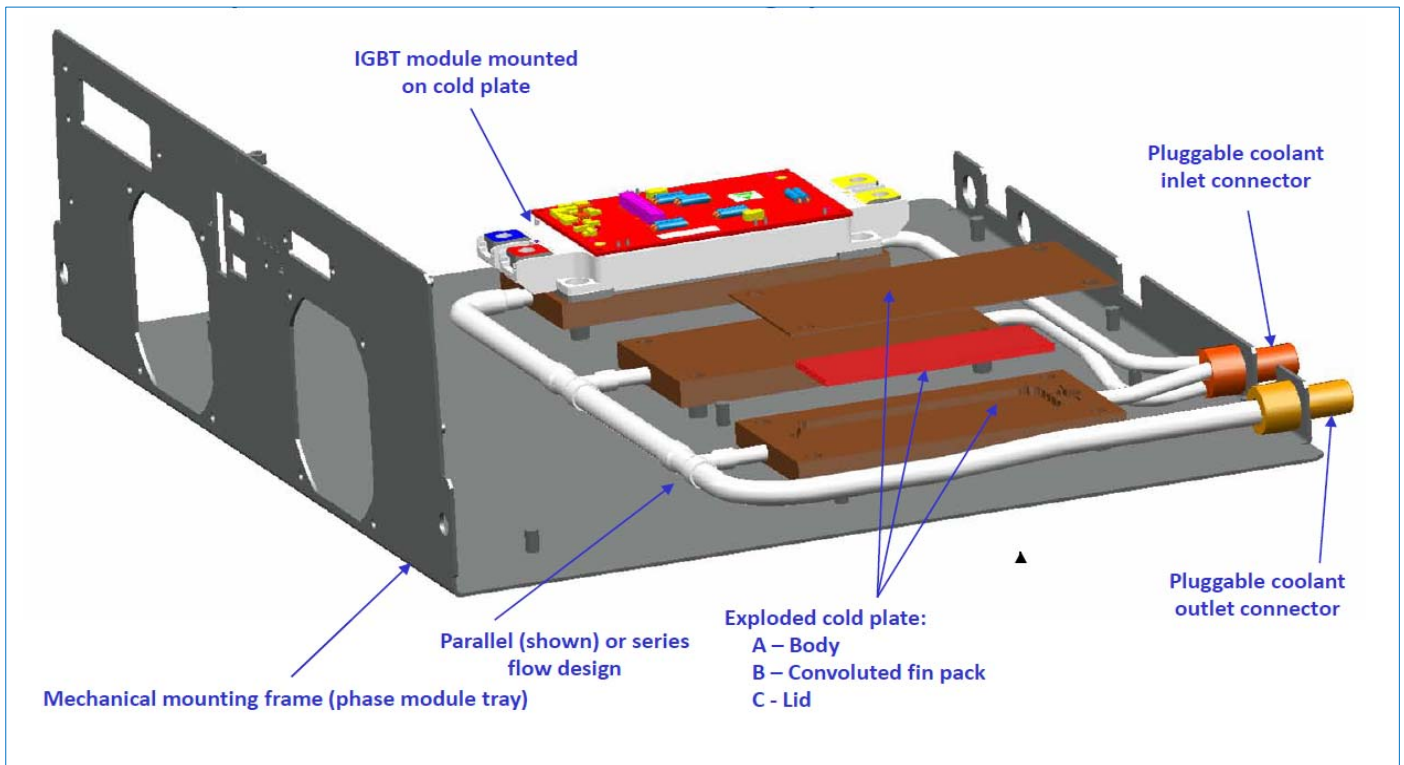


Figure 3: IGBT Tray, as an example of a modular system design for a stationary electrical drive. Three VDF liquid cold plates in series with 1700VAC IGBT modules, fluid line quick disconnects for inlet/outlet flow, and sheet metal tray carrier. One liquid cold plate shown in with IGBT mounted.

an infrared camera.

Maximum module load was measured for each type of cooling solution employed in the prototype assembly, to produce a maximum allowable IGBT junction temperature of 120°C.

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

1. 100% steady-state load;
2. Load condition with 220% overload capability for a 10-second duration.

Overload capability is important in routine operation of power semiconductors utilized in industrial motor drive systems, traction drive systems, and other commonly-occurring situations. The ability of the thermal management solution to handle expected overload conditions is important to avoid catastrophic failure; this overload condition was taken from a selected traction market requirement.

C. Thermal Solution Description and Test Cases

Five basic thermal solution concepts were tested for operation in this drive system. These concepts included current production air-cooled components and newly-developed cold

plates. Individual thermal solutions are identified by case as shown with a brief description in Table 2.

IV. PRACTICAL CONSIDERATIONS IN VDF-COOLED POWER ELECTRONIC SYSTEMS

A. System Design

System hardware design with the VDF cooling loops has several positive attributes, described below. Cost comparisons and analysis may be the subject of a separate discussion in the future as production experience is gained over a number of system designs. Initially, approximations have been estimated for the purposes of providing a reasonable summary of cost and other major attributes.

A single modular IGBT tray assembly is shown in Figure 3, which is a single phase of the three-phase electrical drive. This tray assembly is the basic building block for a modular approach to a set of similar system designs for an OEM electrical drives manufacturer.

Placement of common components in these modules with all thermal solutions at the base of a common platform allows for the interchangeability of heat sinks and cold plates for the

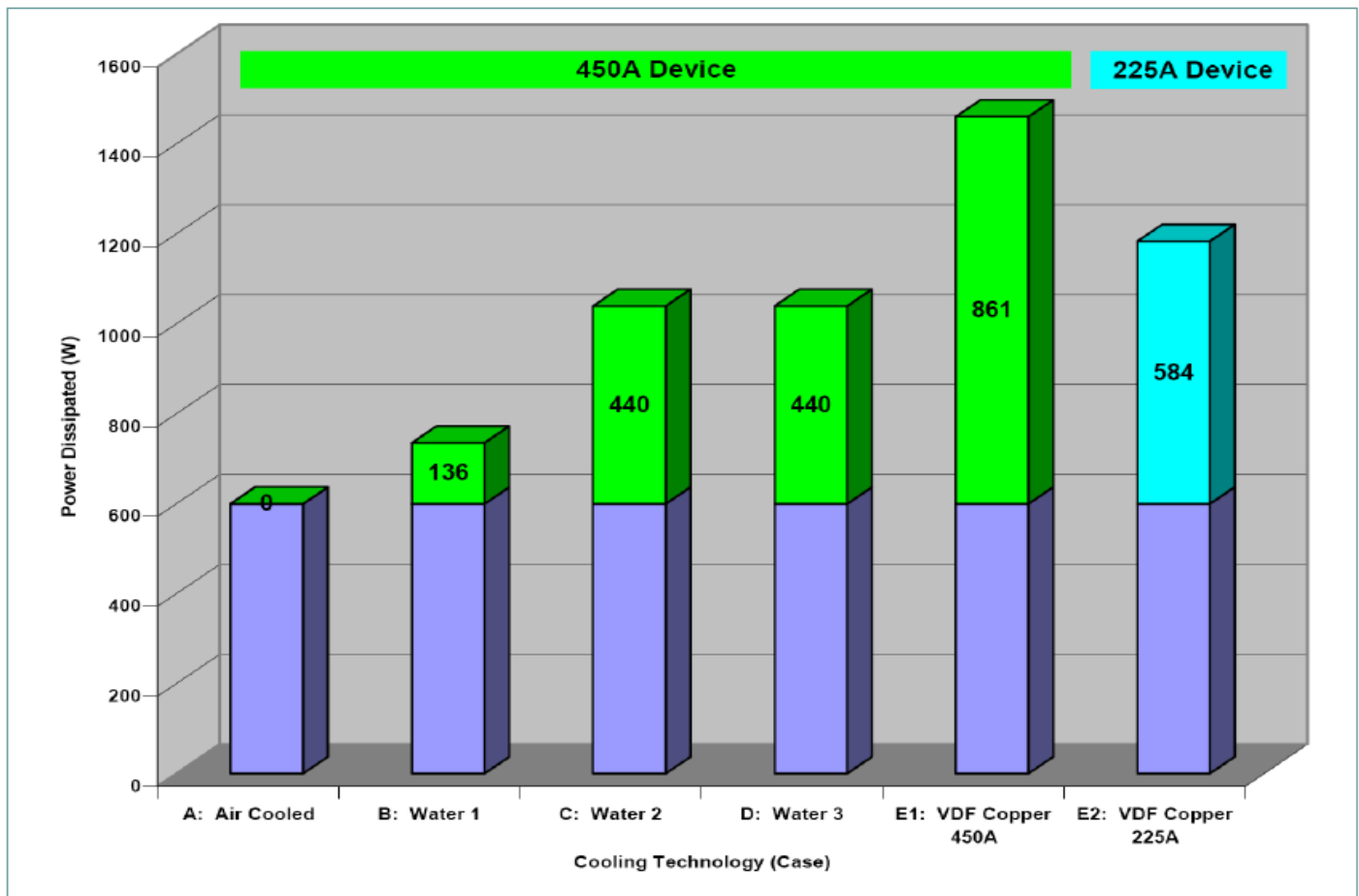


Figure 4. Thermal performance comparative values versus selected thermal management technologies, for a 750kW/1000HP inverter drive system employing standard 1700VAC IGBT modules. Refer to Table 2 (below), for descriptions of individual thermal management technologies tested.

various thermal solutions tested.

Tested electrical drive systems built using this VDF cooling system are shown to require very low fluid flow rates, compared to the use of water cooling (Table 2.)

Case	Thermal Solution	Description	Fluid Flow Rate per Cold Plate LPM (GPM)
A	Forced air cooled extruded heat sink	Aluminum, 14:1 fin ratio, 150CFM airflow	N/A
B	Water-cooled liquid cold plate, standard	Press-fit copper tubing in aluminum body	7.57 (2.0)
C	Water-cooled liquid cold plate, custom	D-shape copper tubing circuit aligned to die locations	7.57 (2.0)
D	Water-cooled liquid cold plate, custom	Convolute Al fin pack, vacuum brazed machined Al surface	7.57 (2.0)
E1	VDF R-134a pumped liquid cold plate (450A IGBT)	Convolute Cu fin pack, brazed, machined Cu surface	1.51 (0.4)
E2	VDF R-134a pumped liquid cold plate (225A IGBT)	Convolute Cu fin pack, brazed, machined Cu surface	1.51 (0.4)

Table 2. Inverter test cases. See also, Figure 3, Thermal Performance Results.

Tested pump parasitic power draw is lower as compared to a traditional water cooling system. Pump power consumed to cool a 1kW load with an all-copper liquid cold plate for the heat source in a VDF system was measured as 12W. An equivalent load in the same system with the water cooling system (Case B, described in the inverter test cases shown in Table 2) using aluminum liquid cold plates is 295W. Parasitic losses for pumps and fans are reduced in the VDF-cooled systems.

Details of liquid cold plate analysis completed for a variety of internal cold plate constructions can be found in a separate presentation. [5]

Additional details on electrical drive system testing, showing system construction and comparative test data for various cooling technologies (cases summarized in Table 2, with results shown in Figure 4), may be found in the literature. [6, 8] Electrical drive systems of this type utilize industry-standard 1700VAC 450A and 225A IGBT devices mounted in stationary drive cabinets used in manufacturing plants and for electrical transmission and power quality systems and other industrial applications.

A typical drive system may be composed of one or more industry-standard enclosures measuring, as an example, 500mm (wide) x 600mm (deep) x 2000mm (high). Use of the VDF cooling system concept has been demonstrated to reduce

physical volumes (as compared to air-cooled and water-cooled systems) from approximately two and one-half cabinets to one cabinet.

Reductions in enclosure volumes of this magnitude also reflect the potential for component and cabling and bus bar complexity, and therefore cost, with the application of such an improved thermal management system. The elimination of certain clearance and creepage requirements and insulation, given the use of a dielectric fluid versus a water-based cooling system, is an additional attribute of the VDF system implementation.

A demonstrator system for laboratory testing is shown in Figures 5-7. Certain components are identified with an asterisk (*) which are sensors and flowmeters for data acquisition in the demonstration hardware, which would not be incorporated in a commercial system design. Systems of this type have been constructed for electrical drives up to 18-27kW in total power dissipation.

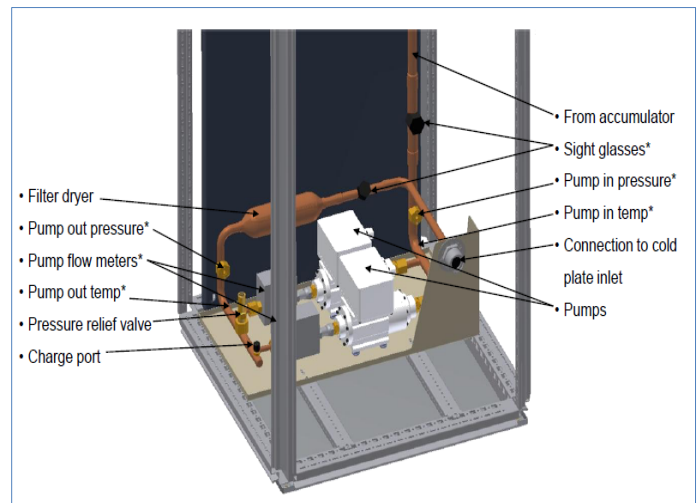


Figure 5. Demonstrator system showing modular concept for major subassemblies: pump module. [Note: Asterisk (*) identifies components installed for data acquisition purposes. Not all components, such as a filter/dryer, are necessarily required for production system designs.]



Figure 6. Liquid-to-liquid condenser module installed in demonstrator system with additional sensors and metering components.

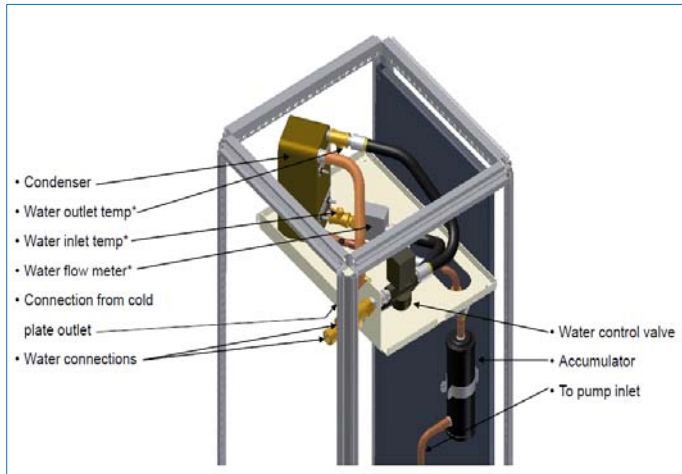


Figure 7. Compact liquid-to-liquid condenser mounted in modular tray with quick-disconnects, for remote mounting from inverter system enclosure.

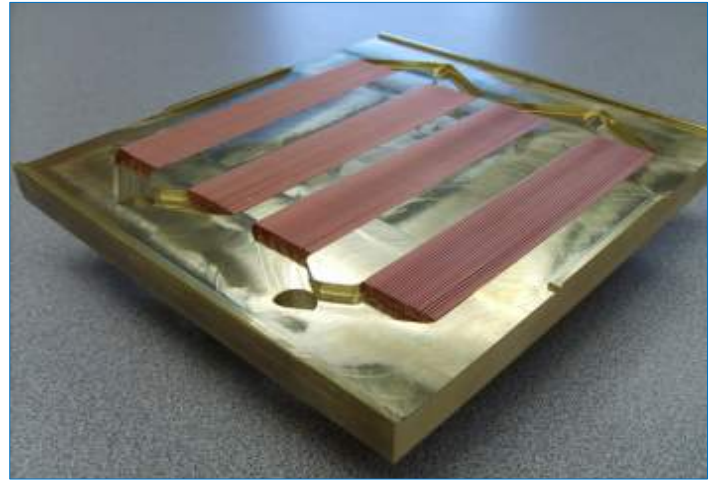


Figure 9. VDF liquid cold plate, illustrating fluid manifolding and flow path through copper convoluted fin packs within brass cold plate body (prior to final cover plate assembly and brazing). Design for 140mm x 130mm IGBT module mounting for vehicle HEV powertrain inverter testing

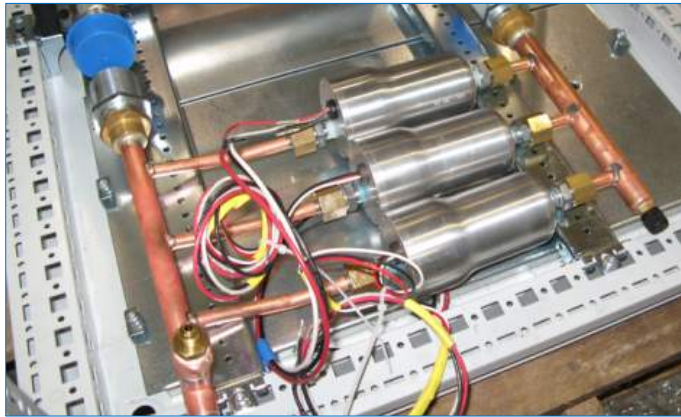


Figure 8A. Multiple small dielectric fluid gerotor pumps in pump tray module with quick-disconnects (two primary, one redundant per system design specification.)



Figure 10. VDF liquid cold plate modular tray assembly for stationary electrical drive, illustrating multiple cold plate mounting for individual 1700VAC IGBT devices in a single phase. Serial flow arrangement shown.

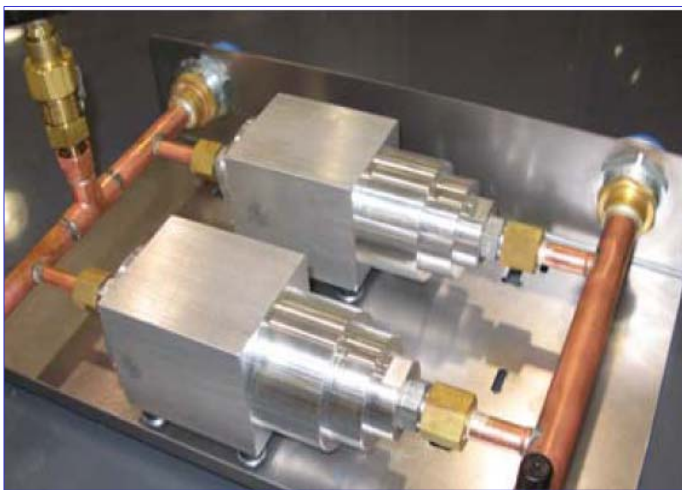


Figure 8B. Two medium capacity dielectric fluid pumps in pump tray module (one primary, one redundant per system design specification). Pump tray equipped with quick-disconnect fittings.

V. PRACTICAL FUTURE APPLICATIONS

A. Many Potential Applications

Applications for a pumped two-phase liquid cooling system as described may be found in a variety of industry segments, where IGBT power semiconductors are used. These include:

- Electrical drives, three-phase, for power quality and power transmission systems
- Electrical drives, three-phase, for motor drives
- Vehicles in construction and off-road, mining, and similar segments
- Electric multiple unit (EMU) trainsets for heavy rail transit systems
- Instrumentation
- Military and radar systems
- Energy storage systems

B. Requirements Leading to Future Applications

Practical applications for a VDF system are expected to be driven by requirements for:

- High power density
- Where a separate liquid coolant circuit can be used;
- Where weight and size are important or must be reduced;
- Power semiconductor systems with high cyclical loads;
- Power inverters and energy storage systems where power densification is required and internal self-heating must be minimized;
- Where multiple loads in a coolant circuit will benefit from reduced thermal stacking;
- Where use of quick-disconnect coolant connectors and a dielectric fluid is advantageous in close proximity to high voltages.
- Potentially higher reliability

C. Future Challenges

Future challenges with use of silicon carbide and other wide bandgap power electronic devices which may be met with a VDF cooling circuit must include evaluation of the

higher operating temperature capabilities of silicon carbide devices, potential for use in double-sided cooling, and other alternative semiconductor packaging.

Availability of very common refrigerants such as R-134a, the current global standard for refrigeration, must also meet standards for reduction of environmental concerns. The development of new, low-global warming potential (GWP) refrigerants such as HFO-1234yf is underway with target dates to meet automotive industry requirements. The intention of such fluids is that these will be “drop-in” replacements for existing refrigerants such as R-134a, for use in automotive cabin air conditioning systems and other applications. HFO-1234yf is expected to be, therefore, a “drop-in” replacement available for VDF cooling systems. [9, 10, 11]

A third opportunity with the use of a VDF cooling circuit or any dielectric coolant is the potential to more fully integrate liquid cooling directly into the power semiconductor module, if device manufacturers perceive value in reducing the number of packaging materials, such as the IGBT module baseplate, and the corresponding reduction in thermal interfaces and thermal resistances.

VI. CONCLUSIONS

Development and use of a pumped vaporizable dielectric fluid cooling system has been evaluated for power electronics systems.

An IGBT electrical drive system based on 1200VAC 450A devices has been assembled, tested, and described with air, water, and a vaporizable dielectric liquid used in subsystem modules to demonstrate proof-of-concept for the VDF-cooled system and determine relative thermal performance improvements. Test systems in stationary electrical drives (non-vehicle) have shown the opportunity to achieve significant volumetric and weight reductions. Thermal performance test results show significant increases in total power dissipation for standard IGBT modules in demonstration systems. Physical volume reduction with the VDF-cooled system concept is as great as 2.5:1, when compared to other thermal management technologies tested.

The proof-of-concept system for this development project is cooled with pumped R-134A refrigerant, an HFC. The use of a vaporizable dielectric fluid of this type at saturation allows the use of a smaller quantity of liquid (one-sixth the mass flow), a smaller pump for low-flow operation, and smaller tubing diameters, when compared to a comparable water cooling system designed for use within the same type of cabinet and to dissipate the same module heat loads. Other vaporizable dielectric fluids are available for use and in development.

Comparative data for air, water, and VDF cooling hardware is presented. The use of a vaporizable dielectric fluid in an copper cold plate with convoluted fin internal structure is

demonstrated to yield 96% additional capacity to dissipate heat generated at the IGBT module base, as compared to the next best water-cooled cold plate tested; the improvement over the production air-cooled finned aluminum extruded thermal solution is demonstrated to be greater than 125%. The system design utilizing VDF cooling also allows consideration of the 225A IGBT module in place of the 450A module, with lower total cost of silicon for the system.

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NOTE

Concepts discussed in this manuscript are the subject of issued and pending US and foreign patents for Parker Hannifin Corporation and Thermal Form & Function, Inc.

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