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Vaporizable Dielectric Fluid Cooling for Military Ground Vehicle Hybrid Powertrains and Energy Storage

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ABSTRACT

Adequate heat dissipation and temperature control for power electronics are critical requirements for vehicle electrification systems, to enable greater power density, reduce size and weight, and improve system performance and reliability. Substantial improvements in heat removal with an advanced thermal management system can impact power semiconductor device operation, module and system power density, and system reliability.

This presentation describes development, testing, and implementation of an innovative two-phase, mechanically-pumped fluid cooling system for power electronic systems which uses a common fluid available in military logistics chains. Attributes of this Vaporizable Dielectric Fluid (VDF) cooling system concept are listed, in comparison to traditional air- and water-glycol cooling systems, with major advantages for overall performance improvement of the power electronic systems for hybrid drivetrains. This system concept has been developed and recently commercialized in a variety of critical power electronic systems.

Intended to be designed as a system rather than as individual discrete components developed by independent vendors, optimization for specific operational requirements overcomes traditional concerns in two-phase operation for dry-out potential and bubble blockages, with balanced design for multiple heat sources with low thermal stacking, extreme temperature capability, dynamic optimization with changing loads, and other criteria. Power density increases of up to 40% have been demonstrated with this sealed, hermetic cooling system.

Advantages for implementation in heavy vehicle power train electrification and for export power and similar electrical systems are explained, with examination of appropriate coolants for military logistics systems in a sealed, pumped system which requires no maintenance.

INTRODUCTION

Commercial and military electronics industry development programs continuously seek to identify and develop improvements within such systems. These are typically incremental improvements by vendors applied at every level from the semiconductor die, the primary electronic component and the source of energy dissipated as waste heat, to the final application of power output to the traction motor.

Implementation of an advanced, system-level thermal solution illustrates that a paradigm shift may be achieved in overall system operational goals, with thermal and electrical design concepts applied as a system-level conceptualization for step-function improvements in power semiconductor performance and system power density. A system-level approach is needed to replace the current highly Balkanized electronics industry practice that focuses solely on discrete, incremental improvements by individual component vendors.

POWER SEMICONDUCTOR EFFICIENCY AND THE ROLE OF THERMAL MANAGEMENT

Implementation of military hybrid and electric vehicle powertrains and energy storage requires development of power electronic and electrical machine (PEEM) system components with very high relative power density, with high electrical efficiency and maximized thermal management to achieve:

a. Efficient removal of waste heat from multiple loads;
b. Minimized semiconductor die area and implementation of precise, optimized heat removal, to reduce packaging and subsystem volume;
c. High overall power and cooling system performance to provide adequate power under demanding operational conditions;
e. Reliable, continuous operation under extreme conditions of temperature, vibration, shock, and other environmental stresses.

The power electronic systems necessary to implement vehicle drive electrification, applied to a military vehicle platform, require development of a high voltage power architecture that includes a traction drive and some form of energy storage subsystem. This high voltage power network must be implemented separately from the existing traditional low-voltage power system which powers vehicle systems such as fuel pumps, lighting, oil and water pumps, etc. The high voltage power network can be considered to be the electrical backbone of the vehicle platform and must be kept electrically isolated from the low-voltage electrical system and the vehicle chassis. Regardless of vehicle electrification architecture, the typical high-voltage network for military vehicle platform development consists of inverters, converters, traction motors, and energy storage subsystems which must be effectively cooled.

The most basic building block for each of these system and subsystem components, with the exception of the traction motor, is the power semiconductor. Power semiconductor modules, typically isolated gate bipolar transistors (IGBTs), are increasingly efficient as the direct result of continuing incremental improvements by power semiconductor manufacturers. A typical value stated for a standard module manufactured with silicon die and packaging technology may be 97% efficient, in normal operating conditions. The remaining 3% of total power is ejected from the module as waste heat. Control of the waste heat is the primary requirement of the thermal management materials and systems employed in the PEEM subsystems, the export power system, and high-voltage power net.

Heat removal and temperature stabilization have long been identified as critical elements in developing increasingly reliable electronic systems. (1) A major objective for development of silicon carbide power semiconductor devices, to replace silicon devices, is to employ the high dielectric breakdown field, high relative thermal conductivity, high temperature tolerance, and wide band gap capabilities of SiC semiconductors for vehicle electrification. When properly applied, these SiC attributes are expected to result in operation of future modules at significantly higher temperatures, with higher frequency passive components, to enable significant reduction in physical size of passive components and reduction in size of the cooling system required, to reduce overall inverter or converter system size and weight. (2, 3, 4)

Maximizing performance of SiC modules by taking full advantage of high temperature and other operating characteristics requires that all materials required to manufacturer complete modules must be developed. Here also, discrete incremental improvements in the substrate, joining, power interconnect, and package materials are being developed at all levels within the electronics industry by suppliers.

Development and implementation of advanced thermal management systems will allow significant improvements in overall electrical system performance, electrical-thermal system size and weight, and system operating reliability.

TYPES OF THERMAL MANAGEMENT SYSTEMS

Heat Pipe and Thermosyphon Cooling

Electric drives have made wide use of heat pipes as a thermal solution. A heat pipe is often referred to as a passive solution as no rotating mechanical device, either a pump or a fan, is required. With a very small quantity of water sealed within the copper tube of the heat pipe, vaporization and condensation occurs in separate regions. Capillary action draws the condensing liquid and the vaporization and condensation cycle repeats without application of a mechanical force, when there is sufficient heating at the vaporization end of the heat pipe. (5, 6) Vapor chambers and capillary pumped loop (CPL) systems operate on the same principle. (7, 8, 9)

Heat pipes, capillary pumped loops, and thermosyphons offer the reliability advantage of no pump motor,, as the first step beyond traditional forced-air cooling systems. (10)

Single-Phase Liquid Cooling

Active liquid systems with a coolant pumped through one or more liquid cold plates for heat removal and dumping the load to either liquid-to-liquid or liquid-to-air heat exchangers, are the dominant global liquid cooling concept.

Mechanically-pumped liquid cooling of power semiconductors is used globally in single-phase operation at moderate pressures with water/glycol or deionized water as the primary coolant. Liquid cooling for power electronics initially used dielectric oils; the first applications included, for example, large transformer windings. Later development of compression-clamped thyristors packaged with electrically-live pressure contact surfaces utilized single-phase liquid cold plates or direct liquid immersion with perfluorinated fluorocarbon dielectric liquid coolants.

Reasons for wide use of single-phase pumped liquid cooling systems include the perceptions of system simplicity; the ability to expand system capacity by adding duplicate components (primarily cold plates, given sufficient condenser capacity) or by improving the thermal design of a given component. There is wide availability of components from many vendors globally, in high volume production. Mechanical engineering university curricula typically always includes exposure to basic thermodynamics coursework and the single-phase pumped system concepts. Single-phase performance is relatively simple to propose and model.

Direct Liquid Immersion Cooling and IGBT Packaging Requirements

Direct liquid immersion with dielectric fluids is less well-known, less understood, and sometimes regarded as inherently more complex and more expensive. While these are factors in system design when examining the basics of the concept, a more important detriment is the lack of power semiconductor devices designed for use in such systems. The first AC electrical drives for heavy off-road vehicles, designed with liquid immersion cooling, were based on compression-pack GTO devices. While this concept remains quite valid and production of such assemblies has continued for more than twenty-five years, the industry transition from compression-clamped GTO, diode, and thyristor devices has changed the basic format of many device packages. Most power transistors considered for current HEV/EV powertrain inverters are of the more recent IGBT and FET power semiconductor device types. These standardized package types are specifically designed with flat electrically-isolated mounting surfaces, designed for attachment directly to an air- or liquid-cooled heat sink. The development of the standard IGBT module packaging concept has driven wide development and use of standardized heat sink and liquid cold plate designs to provide a thermal path, at the same time allowing multiple vendors to follow the standardized format for cost purposes with multiple sourcing.

These packaging technologies have received very high levels of continued research and development, to continuously improve electrical, mechanical, thermal, and reliability performance. These incremental steps follow the same relatively standardized and widely-used IGBT package format.

Use of a direct liquid immersion technology, while offering the possibility of large improvements in heat flux capability, heat transfer, and device reliability, also requires development and testing of power semiconductor packaging in a minimalist format. The minimalist packaging format required would strip away many of the packaging materials and standards that have been developed by the industry, which would again require manufacturers to make major changes in system and device designs. Cost of dielectric fluids is also perceived as a barrier. Perception of the simplicity of single-phase liquid cold plate designs, and the relatively high heat capacity of water versus many dielectric fluids, has constrained development of immersion cooling on a wide scale.

MARKET REQUIREMENTS FOR IMPROVED IGBT SEMICONDUCTOR COOLING

Continued increases in overall power density requirements for electrical drives across global industrial markets are driven by increasing use of electrical energy for a range of applications, at the same time as multiple factors press for improvements in reliability and reduction in system cost and size. Electrification of vehicles is one of the industry markets where these hurdles are increasing the importance of advanced thermal management technologies to achieve increased system density, reduction in size and weight, and improvement in power output. Implementation of SiC and other wide band gap devices, while offering higher operating temperature and other improved characteristics that aid in addressing these requirements, also incurs significantly higher semiconductor costs across the system. This combination of circumstances is driving the need for step-function improvement in thermal management.

Further, increased attention globally to driving energy efficiency forward is creating additional demand for more efficient power electronics, as well as more efficient thermal management of these systems. For thermal engineers, to respond simply with larger single-phase liquid volumes, larger heat exchangers, and higher-performance cold plate designs represent the traditional, incremental improvement which has been a constant effort. The barriers that this approach faces are the need to minimize cooling system volume and weight, in direct opposition to this traditional approach. Critical volume and weight requirements for military vehicle electrification and battlefield power systems make these limitations obvious.

MECHANICALLY-PUMPED TWO-PHASE COOLING

Application of the heat of vaporization principle used in a heat pipe or vapor chamber in a mechanically-pumped two-phase cooling system provides substantial increases in heat removal capability, while requiring lesser volumes of coolant in smaller, more efficient components. Development of mechanically-pumped two-phase systems has traditionally been stymied by perception of increased complexity, lack of appropriate pumps designed for two-phase systems, and industry perceptions of inherent instabilities in water-based systems with inadequate design.

The traditional electronic industry practice of applying incremental change has led to misappropriation, for example, of microchannel cold plate designs in application to water-based systems. Especially in vehicle applications, use of water (typically, ethylene glycol/water mixtures, EGW) from the internal combustion engine (ICE) coolant system, has resulted in bubble formation, particulate blockages, and other sources of instabilities in system operation with microchannel liquid cold plate construction. Recent university research addresses microchannel construction and related instabilities. (11) However, practical requirements for automotive industry requirements have led to IGBT and automotive inverter manufacturers requiring a minimum of 1mm spacing for coolant channels, to eliminate particulate blockage potential.

Investigation of alternative coolant fluids and system concepts has led to development and recent commercialization of systems termed as Vaporizable Dielectric Fluid Cooling (VDF).

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This system concept, utilizing a commonly available fluid with properties that have proven to be advantageous for two-phase systems, is being used to mount and cool IGBT modules in a variety of electrical drive applications. A case study, developed by an early adopter in the commercial electrical drives industry, developed comparative thermal test performance for air-, single-phase water, and VDF-cooled solutions. Case study results for the three cooling technologies compared showed that significant reductions in overall volume and weight occupied by mechanical components, with implementation of the VDF cooling system, enabled a substantial reduction in overall drive system cabinet volume, from three cabinets to one. (12)

VDF Basic System Components

The basic VDF system consists of:

- A low-flow rate refrigerant liquid pump;
- Refrigerant fluid filter to ensure clean fluid circulation without moisture;
- Liquid cold plates in series or parallel, cooling heat sources which may be IGBTs, transformer coils, electric motors, or battery arrays;
- Condenser: A standard fluid-to-air or fluid-to-liquid heat exchanger, used to remove heat from mixed-phase refrigerant;
- Accumulator, used to store excess refrigerant and compensate for volume changes;
- Hosing or tubing: Common refrigerant-grade flexible hosing or hard-plumbed copper tubing;
- Dry-break couplings of a variety of types, integrated as needed for system components.

A feature of VDF systems for electronics cooling is the low flow rate required, with an example described in Table 1 (below). The relatively low fluid flow rates necessary to maintain the same level of cooling as compared to water-based systems, is approximately one-fifth the flow rate required for a single-phase EGW system. Further, a smaller quantity of coolant is required, again as compared to water (EGW, deionized, or deionized water/EG) systems.

VDF systems operate at higher pressures for electronics cooling applications as compared to a water-based system, but pressures are moderate and easily managed in proper system design.

Advantages for Power Electronics Cooling

Several important advantages accrue for electronics system cooling, with the use of a mechanically-pumped dielectric fluid system using a dielectric refrigerant:

- Use of heat of vaporization principle to reach very high efficiencies of two-phase heat transport with reduced fluid flow rate;
- Low parasitic energy consumption for pumps, with low fluid flow rates and low pressure drop;
- Dynamic optimization during system operation: the VDF system balances dynamically with increasing heat loads causing increased rate of boiling with the cold plates. Similarly, the rate of boiling reduces as the heat load is reduced.
- Highly-scalable system design;
- Isothermal liquid cold plates with relatively small temperature differentials across multiple heat sources (typically, less than 1°C);
- Elimination of system balancing concerns with a system approach to design and proper manifold and flow design, with either series or parallel cold plate operation;

- Elimination of galvanic action and corrosion due to ionic contamination, even with mixed metals within the system, as R-134a is an inert dielectric;
- Personnel safety concerns are eliminated with the a non-toxic fluid which vaporizes upon contact with heat sources and electronics;
- Catastrophic electronic/electrical system failure due to coolant shorting, in the event of a leak, is eliminated;
- Inert dielectric fluids are compatible with a wide range of materials used to manufacture seals, hosing, tubing, quick-disconnect fittings, manifolds, and other components. Thousands of different types of hosing, seals, tubing, and other components are available from refrigeration system vendors with known permeability ratings, reiliability, and low costs reflecting long-term, high-volume manufacturing.
- Elimination of periodic coolant refilling; elimination of maintenance requirements for deionizing system cartridges and filters;
- Designed as a sealed system shipped completely flushed and filled with coolant within an enclosure.

SELECTION OF PROPER FLUIDS AS COOLANTS

A general statement may be made that within the electronics industry, broadly defined, predominant fluids used are specific to individual market segment by equipment type. For example, in the automotive industry, commercial vehicle OEMs have traditionally targeted the use of the coolant immediately available from the ICE cooling loop; this is most typically EGW with an expected inlet temperature of 105°C. This inlet coolant temperature presents a very challenging thermal design task, as maximum typical IGBT die junction temperatures are in the range of 125-150°C, allowing little operational headroom for heat removal.

Current development and production HEV/EV vehicles generally use secondary coolant loops, however, with lower maximum inlet temperatures (typically, 65-85°C) and consisting of EGW with inhibitors. EGW is considered to be toxic. Propylene glycol/water (PGW) mixtures are an alternative that is considered to be non-toxic, but with higher viscosity and higher cost. Use of a secondary coolant loop is expected to continue for HEV and EV powertrains, as a general statement, until IGBT module improvements allow operation at higher maximum temperatures and the use of the ICE coolant at 105°C. (13).

As another example, North American military airborne platform electronics currently use an aliphatic, polyalphaolefin (PAO), as a common coolant, generally seen as a preferred selection. PAO as a more stable fluid largely replaced the use of silicate esters such as Coolanol™ in older systems.

Stationary power equipment in industrial markets for energy conversion, transmission, and application in electrical drives typically use either single-phase water or single-phase deionized water, with or without glycol, with additional inhibitors applied as needed.

A very common justification for the use of water as an electronic coolant is the known high relative heat capacity of water; a large number of liquid cold plates, heat exchangers, pumps, and other components are available from a global base of established vendors, many competing heavily on price at different levels of perceived reliability.

The wide global availability of unfiltered, untreated water is perceived as representing a supply of a no-cost coolant for many applications. This is significantly misleading, as many requirements exist for relative purity, lack of corrosivity (through use of inhibitors), lubricity, and frost-proofing for outdoor applications.

Additives are required for most water and deionized water cooling systems. These additives typically are used for:

- Frostproofing, for operation in extreme outdoor ambient temperatures (low and high).
- Biologic growth, scaling, relative pH, and control of other similar chemical and biological degradation during operation.
- Corrosion and galvanic action resistance.

Corrosivity of ethylene glycol can be limited by proper use of inhibitors; EG is considered to be toxic, is completely miscible in water, and is odorless and colorless. Water with low chloride and sulfate ion concentrations is required for electronic systems. (14)

Deionized water requires the design and installation of a deionizing filter cartridge system and the addition of a maintenance schedule for the life of the electronic system, for monitoring and replacement of the filter cartridges. Filter cartridges can be high in cost, depending on size and type. Fully-deionized water is also extremely corrosive to certain metals and materials used in liquid cooling systems and control of the deionization system is required.

An important note is that once inhibitors for pH, biological growth, corrosion, and other chemical changes are depleted, the coolant must be removed and replaced. This is typically a scheduled maintenance requirement for all types of electrical drives, to maintain system reliability and avoid development of leaks due to corrosion and failures due to dielectric breakdown.

Use of additives and deionization add cost, require periodic testing and maintenance, and affect heat transfer capacity of the water coolant. (15)

Commercial Dielectric Fluid Coolants

Dielectric liquids such as 3M Fluorinert™ and the current Fluoroketone chemistries are well documented for semiconductor test equipment, burn-in, and for traction applications in the heavy rail transportation industry.

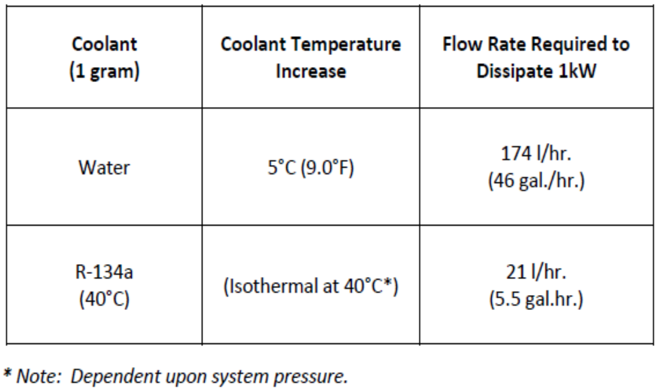
A selection process is required for each of these types of fluids to match electrical isolation requirements, thermal performance, cost, operating temperatures, altitude, and other specific characteristics. (16)

Common Refrigerants as Coolants

Use of a two-phase, mechanically-pumped cooling system using a common refrigerant, R-134a, for a fixed heat transfer task is shown in Table 1, with a comparison to use of water as a coolant. Using the stated assumptions, a reduction in required coolant flow rated from 174 l/hr. with the water system to 21 l/hr. with the VDF system and coolant R-134a is achieved, to dissipate one kilowatt of power.

This result illustrates a major advantage for consideration of a two-phase, mechanically pumped liquid cooling system with a fluid which is selected specifically for operational characteristics in two-phase operation.

Evaluation of an alternative coolant, such as a common refrigerant, for military ground vehicle inverters systems must include the logistical requirements for introducing a new liquid into military supply chains to the battlefield. Selection of a globally-available fluid such as R-134a refrigerant, used for all mobile ground vehicle air conditioning systems and available worldwide from many suppliers, meets the defense industry requirement that a coolant be available through the existing logistical supply chain. R-134a is used as the refrigerant for on-vehicle personnel air conditioning systems for armored vehicle warfighters and is used as the universal refrigerant for ground vehicle air conditioning systems. This is an important factor in meeting coolant selection criteria for global availability at reasonable cost.



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.*

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

R-134a refrigerant has these operating characteristics that are useful in cooling system design:

- Relatively low boiling point, advantageous for electronics cooling applications;
- Extremely low freezing temperature, eliminating any requirement for frostproofing and subsequent thermal performance derating;
- Very high relative vapor pressure;
- Considered to be a non-toxic fluid in reasonable and normal quantities;
- Evaporates harmlessly on contact with hot surfaces;
- Dielectric, with a low dielectric value, evaporating on contact with live electronic components;
- Chemically inert, compatible with most engineered plastics; seals; and other system materials;
- Inert in a mixed-metal system, not promoting galvanic action;
- Relatively high specific heat, as compared to commercial dielectric coolants such as HFEs and fluorocarbon fluids;
- High autoignition temperature; no flashpoint;
- Density not significantly greater than water;
- Relatively low GWP value;
- Available through military logistics supply chains.

Global Warming Potential (GWP) values have been established for many fluids considered or used as electronic coolants. The commonly-available R-134a, with an assigned value of 1400 on the GWP rating scale, is to be replaced with a new refrigerant with a very low value. This new fluid, designated HFO-1234yf, is a joint development project between two major refrigerant manufacturers and available in pilot production today. This new fluid, and the companion HFO-1234ze, both meet the recent European Union directive on the use of refrigerants with lower GWP values for mobile applications (principally, for vehicle air conditioning systems in new automobile production worldwide). [16] Several references are available regarding this new family of refrigerants, designed to offer drop-in-place equivalency of performance and other characteristics. [17, 18, 19]

VDF SYSTEM COMPARATIVE PERFORMANCE IN MEDIUM VOLTAGE ELECTRICAL DRIVES

An example of comparative performance follows for a stationary medium-voltage electrical drive. The baseline system for this comparison is an earlier production version, cooled with the traditional deionized water cooling circuit.

Parameter	Baseline System Design	VDF-Cooled System Design
Heat dissipated: ***System*** ***Transformer***	400kW 70kW	400kW 70kW
Cooling system and coolant	Deionized water with deionization cartridge system	VDF two-phase R-134a
System coolant flow rate	450 GPM	70 GPM
Pump weight	800 lbs.	65 lbs.
Cabinet size	84” H (multiple)	30% reduction (total system volume)

Table 2. Comparative performance achieved in a medium voltage electrical drive with transformer.

Implementation of the VDF two-phase cooling concept to this electrical drive resulted in complete elimination of the deionizing filter system and cartridges and associated requirements for cartridge monitoring and periodic replacement. The VDF implementation also sharply reduced total volume of coolant and coolant flow rates required; achieved a reduction in total weight of pumps and system cabinet volume (as shown in Table 2); reduced total electrical insulation wrapping required for transformer windings; and reduced weight and eliminated coolant flow problems in the transformer core.

Case study analysis of thermal performance for a similar electrical drive has been published previously. (20) A synopsis of results is shown in the Appendix, below. This analysis compared air-, water-, and VDF cooling technologies applied to a production stationary electrical drive. Results indicated that the production design could be revised from a three-cabinet drive to a single cabinet system, with savings on semiconductor device cost with implementation of the VDF system, by selecting 225A IGBT modules in place of 450A devices when utilizing the improved thermal management system.

APPLICATION TO HEV POWERTRAIN INVERTERS

High-performance, compact, and reliable inverter drives for electrification of military vehicle drivetrains require thermal management systems capable of both removing large amounts of heat with high cyclical power loads.

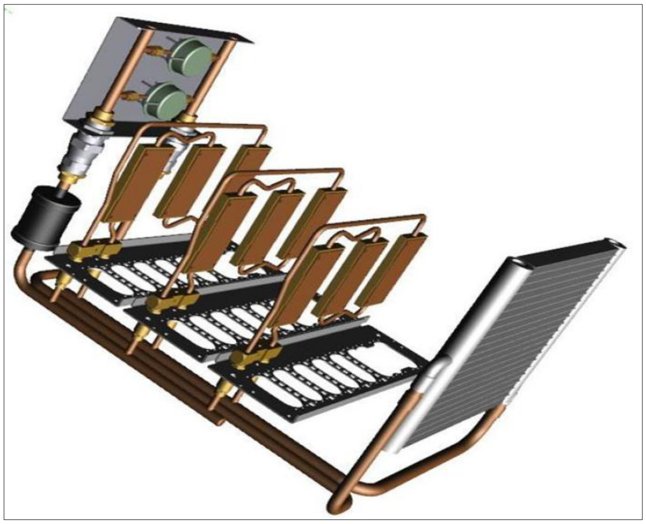


Figure 1: Conceptual layout of a modular VDF cooling system for a military ground tactical vehicle HEV powertrain inverter. Note that each cold plate module consists of three VDF liquid cold plates in series, to mount three standard IGBT modules for this prototype drive.

HEV/EV powertrain market requirements are in the forefront of semiconductor industry development targets to raise maximum die junction temperature capabilities, adapt to higher ambients, and allow higher coolant temperatures.

These industry development activities are not limited to development of silicon carbide semiconductors. Implementation of an advanced liquid cooling system as a secondary loop for powertrain electronics (and, as required, energy storage systems) is a goal for step-function improvements in overall power handling capability regardless of semiconductor technology applied.

Drawing on recent industry experience with the application of VDF liquid cooling systems to stationary electrical drives, development is underway where VDF cooling is being evaluated for certain types of heavy off-road and military vehicle powertrain drives. A conceptual illustration is shown in Figure 1 (above) for a prototype of a module VDF cooling system design for application to a military ground tactical vehicle. The same operating characteristics, fluid characteristics, and operating advantages described for stationary electrical drives apply to these potential mobile applications.

Liquid cold plates utilized for prototype development are termed as “mesochannel” cold plates, intended to describe cooling channels that are greater than the standard 1mm fluid channel demanded by the vehicle industry and other industry segments. Performance of these types of liquid cold plates designed for VDF systems are described in detail elsewhere. [21]

Pumps for these two-phase mechanically-pumped liquid cooling systems have been developed and commercialized as part of VDF system development. These pump designs are significantly smaller than pumps required for water-based cooling systems, are highly efficient and are small parasitic loads on the system, and offer large weight reductions. [22]

APPLICATION TO HEV/EV POWERTRAIN ENERGY STORAGE SYSTEMS

A rapidly-development market requirement for temperature maintenance, as well as heat dissipation, exists for energy storage systems for HEV, EV, and fuel cell powertrains for ground vehicles. Development of HEV and EV powertrains and the accompanying forms of battery and other energy storage concepts includes development of appropriate cooling systems to remove heat and to maintain temperatures between cells. An example of a current VDF system application in development is shown in Figure 2 (below) for an ultracapacitor array to be applied within an existing machine enclosure, for a large international off-road vehicle manufacturer. Energy storage systems have very different thermal requirements, as compared to drives and motors, as the heat fluxes may be quite low and average total heat to be dissipated may appear to be low. Extreme operating conditions and fixed volumes available within a vehicle shell for the energy storage system, within vehicle sheet metal or armor and exposed to full solar exposure in desert conditions, increase maximum ambient temperature conditions to very high level, in some cases exceeding the capability of a water-cooling system to meet total requirements for heat rejections.

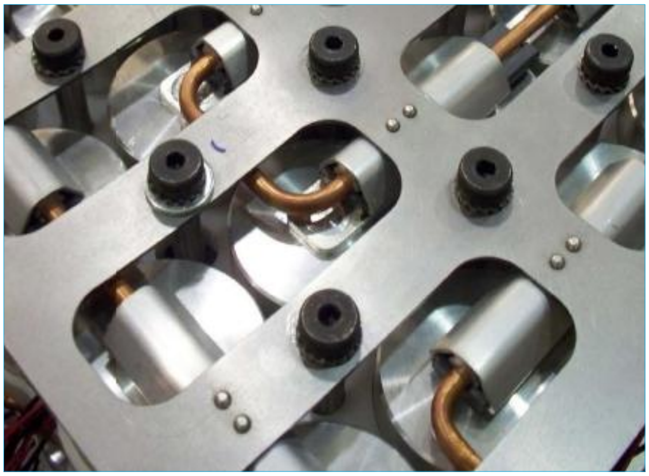


Figure 2. Detail photograph of an ultracapacitor array utilizing two-phase VDF cooling system concept for a heavy off-road vehicle with HEV powertrain.

CONCLUSIONS

Advancements to improve heat rejection capabilities with minimum size, space, and energy consumption for the cooling system can also be used to improve overall system performance, size, efficiency, and cost.

Applications of two-phase pumped dielectric cooling systems are one area where demonstration systems have been assembled and tested and continued development work has led to commercialized systems.

Space utilization, system efficiency, and improvements in IGBT module performance, cost, and reliability can also be achieved with the use of advanced cooling systems. The same system concepts are also being prototyped and evaluated for energy storage systems, to provide highly efficient heat removal and temperature stabilization within cell arrays.

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VDF™ is a trademark of Parker Hannifin Corporation (Cleveland OH USA).

Coolanol™ is a tradename of the former Monsanto Specialty Chemicals Inc.

Fluorinert™ is a tradename of 3M Company (St. Paul MN USA).

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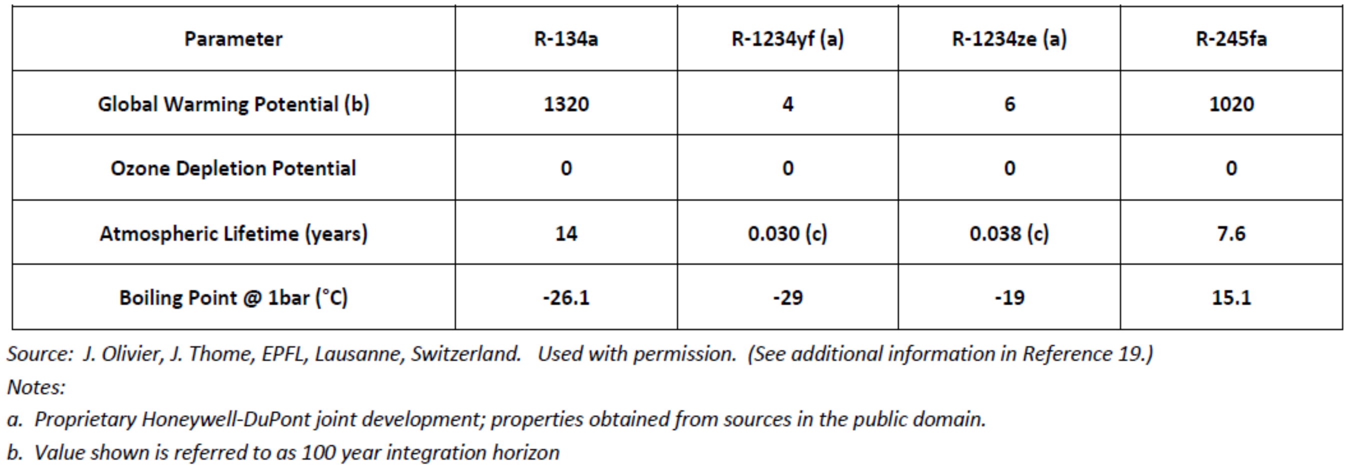
[22] See Appendix, Table B; and documentation at the following URL: www.powersystemscooling.com.

Appendix



Parameter	R-134a	R-1234yf (a)	R-1234ze (a)	R-245fa
Global Warming Potential (b)	1320	4	6	1020
Ozone Depletion Potential	0	0	0	0
Atmospheric Lifetime (years)	14	0.030 (c)	0.038 (c)	7.6
Boiling Point @ 1bar (°C)	-26.1	-29	-19	15.1

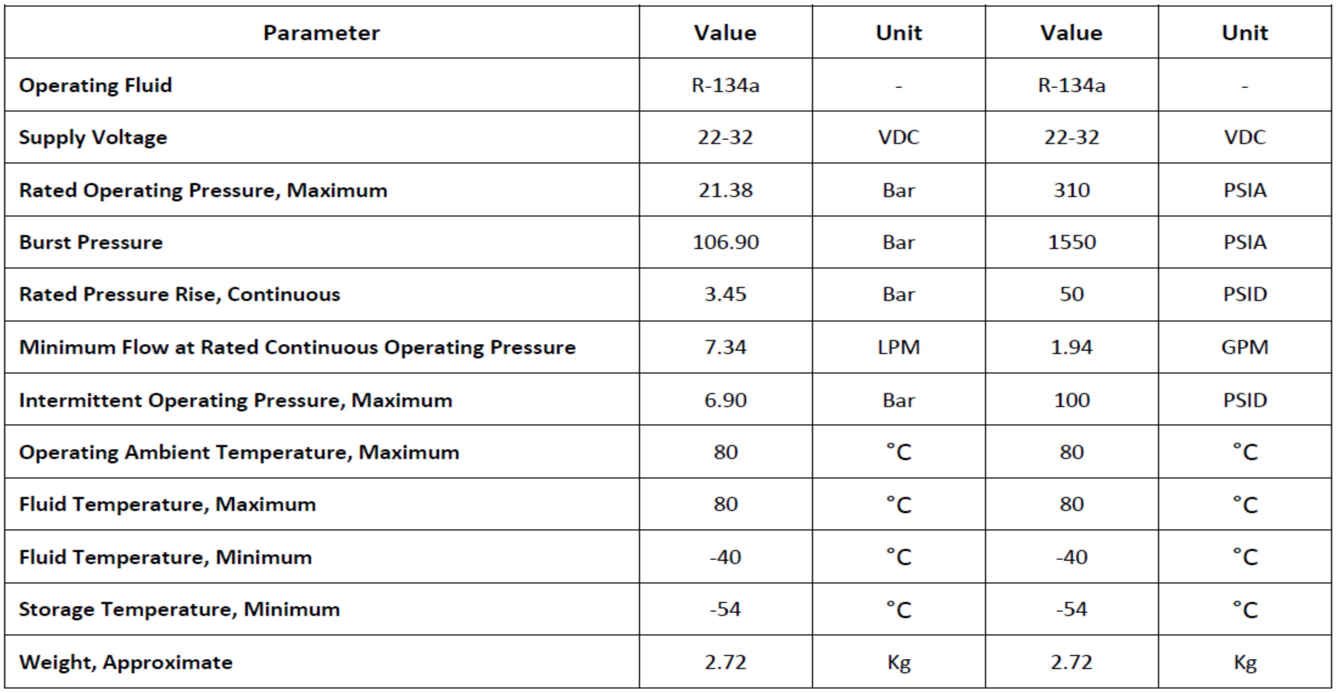
Source: J. Olivier, J. Thome, EPFL, Lausanne, Switzerland. Used with permission. (See additional information in Reference 19.)

Notes:

a. Proprietary Honeywell-DuPont joint development; properties obtained from sources in the public domain.

b. Value shown is referred to as 100 year integration horizon

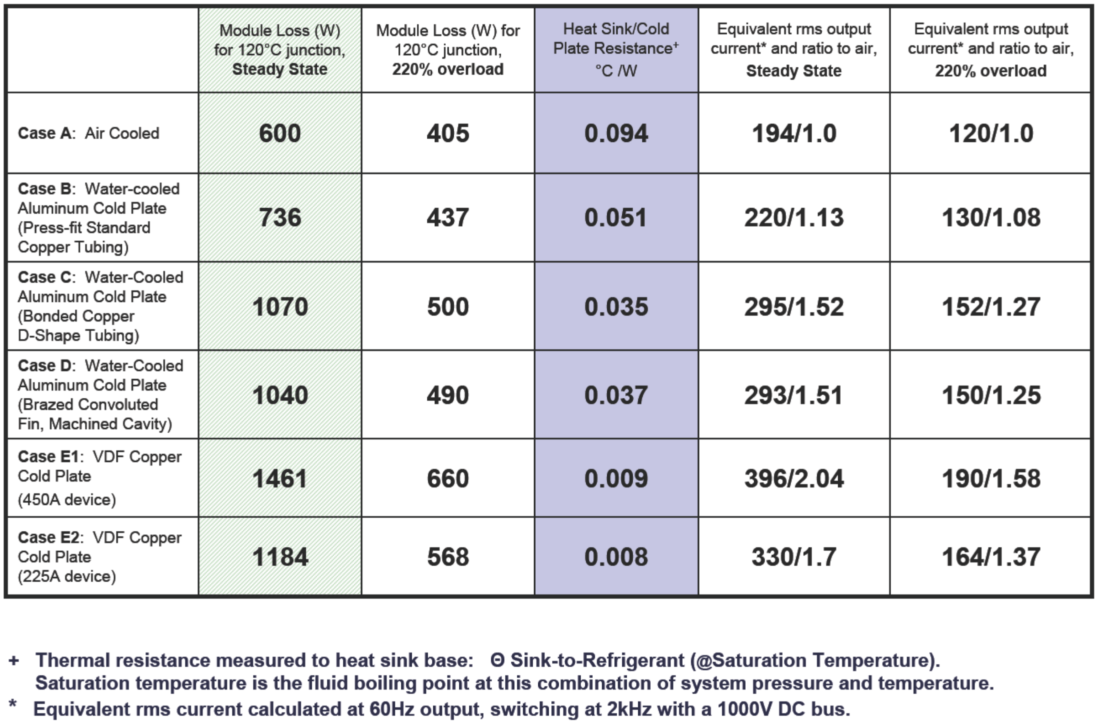
Table A. Parameters for Refrigerants R-134a (and R-245fa) and Low-GWP Replacements R-1234yf and R-1234ze.



Parameter	Value	Unit	Value	Unit
Operating Fluid	R-134a	-	R-134a	-
Supply Voltage	22-32	VDC	22-32	VDC
Rated Operating Pressure, Maximum	21.38	Bar	310	PSIA
Burst Pressure	106.90	Bar	1550	PSIA
Rated Pressure Rise, Continuous	3.45	Bar	50	PSID
Minimum Flow at Rated Continuous Operating Pressure	7.34	LPM	1.94	GPM
Intermittent Operating Pressure, Maximum	6.90	Bar	100	PSID
Operating Ambient Temperature, Maximum	80	°C	80	°C
Fluid Temperature, Maximum	80	°C	80	°C
Fluid Temperature, Minimum	-40	°C	-40	°C
Storage Temperature, Minimum	-54	°C	-54	°C
Weight, Approximate	2.72	Kg	2.72	Kg

Source: Parker Hannifin

Table B. Rated Performance, 17kW Capacity Pump for VDF Systems.



	Module Loss (W) for 120°C junction, **Steady State**	Module Loss (W) for 120°C junction, **220% overload**	Heat Sink/Cold Plate Resistance+ °C /W	Equivalent rms output current* and ratio to air, **Steady State**	Equivalent rms output current* and ratio to air, **220% overload**
Case A: Air Cooled	**600**	**405**	**0.094**	**194/1.0**	**120/1.0**
Case B: Water-cooled Aluminum Cold Plate (Press-fit Standard Copper Tubing)	**736**	**437**	**0.051**	**220/1.13**	**130/1.08**
Case C: Water-Cooled Aluminum Cold Plate (Bonded Copper D-Shape Tubing)	**1070**	**500**	**0.035**	**295/1.52**	**152/1.27**
Case D: Water-Cooled Aluminum Cold Plate (Brazed Convoluted Fin, Machined Cavity)	**1040**	**490**	**0.037**	**293/1.51**	**150/1.25**
Case E1: VDF Copper Cold Plate (450A device)	**1461**	**660**	**0.009**	**396/2.04**	**190/1.58**
Case E2: VDF Copper Cold Plate (225A device)	**1184**	**568**	**0.008**	**330/1.7**	**164/1.37**

+ Thermal resistance measured to heat sink base: Θ Sink-to-Refrigerant (@Saturation Temperature).
Saturation temperature is the fluid boiling point at this combination of system pressure and temperature.

*** Equivalent rms current calculated at 60Hz output, switching at 2kHz with a 1000V DC bus.**

Table C. Thermal Performance Test Data and System Electrical Performance Calculations, Electrical Drive.

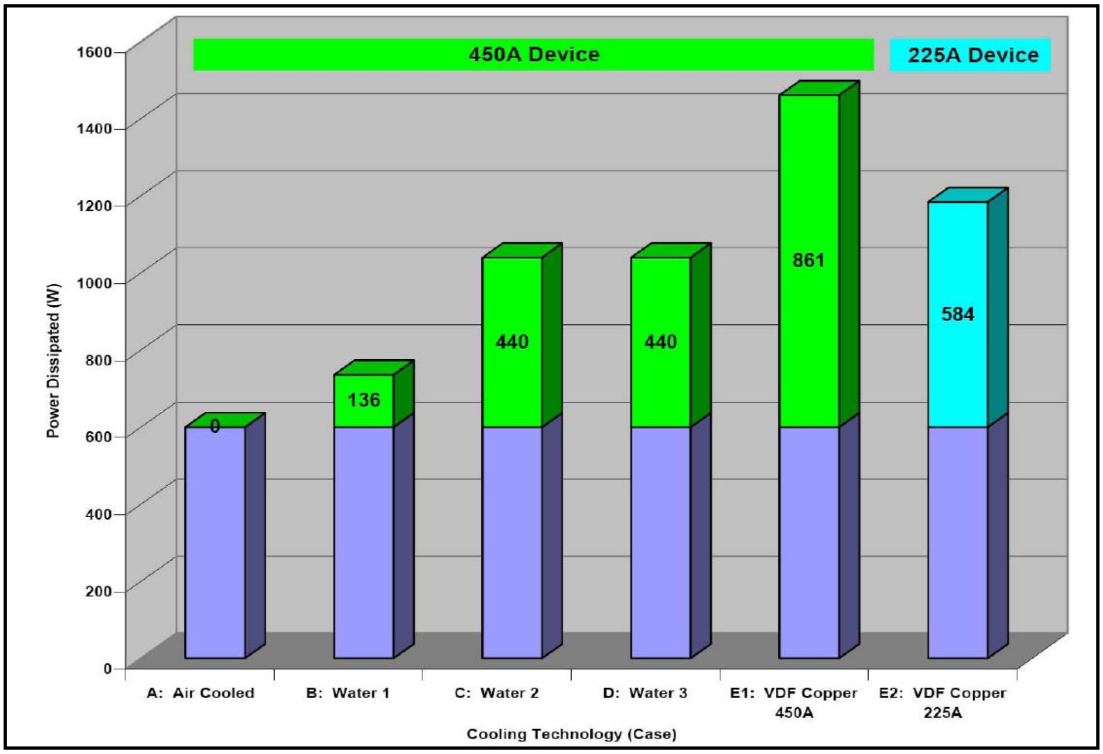


Figure A. Thermal Performance Test Data, Electrical Drive ***(See Table C, Column A for descriptions of hardware for Cases A through E2)***