Enabling Next Generation Data Centers with Two Phase Liquid Cooling

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ABSTRACT

The increasing integration of artificial intelligence in data centers has significantly elevated thermal loads and heat dissipation demands. In response, high-efficient Two-Phase Immersion Cooling (2-PIC) has emerged as a leading solution for managing the thermal challenges of high power-density chips. One key barrier to broader implementation of 2-PIC has been the limited availability of suitable dielectric fluids. This paper presents key attributes of a new low-GWP dielectric fluid, Opteon™ 2P50, developed for 2-PIC applications. Dielectric properties have been evaluated at frequencies up to 32GHz, and signal integrity assessments revealed an insertion loss profile comparable to that of air, and significantly better than the minimum industry standards. This new fluid also demonstrates excellent material compatibility with most plastics and elastomers, along with superior thermal and chemical stability under elevated temperatures, making it a reliable choice for long-term use in two-phase immersion cooling systems. In addition, a comprehensive Total Cost of Ownership (TCO) analysis for a 36 MW data center shows that 2-PIC, particularly with adiabatic fluid coolers, offers a cost-effective and energy-efficient solution for meeting the rising thermal demands of advanced computing workloads.

Keywords: Data centers, Two-phase, Liquid cooling, Immersion cooling, 2-PIC, Total cost of ownership

1. INTRODUCTION

The exponential growth of data-intensive applications—ranging from artificial intelligence (AI) and high-performance computing (HPC) to cloud services and edge computing—has driven a dramatic increase in server power densities and thermal design power (TDP) requirements. Traditional air-based cooling systems, which have long been the standard for data center thermal management, are now struggling to meet the demands of modern computing environments. As a result, liquid cooling technologies have emerged as critical enablers for next-generation data centers, offering superior thermal performance, energy efficiency, and scalability.

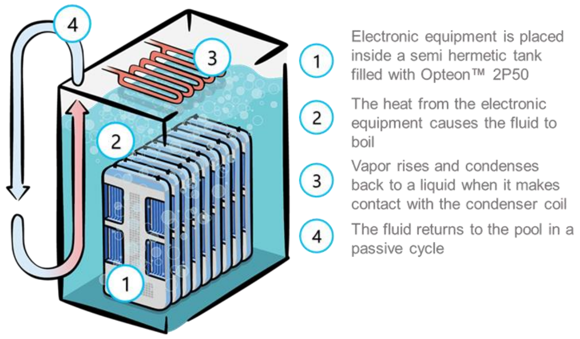

Figure 1: Schematic of the two-phase immersion cooling operation

Among liquid cooling approaches, two-phase technologies—specifically two-phase immersion cooling (Figure 1) and two-phase direct-to-chip (Figure 2)—have shown significant improvements in server temperature control, power usage effectiveness (PUE), water utilization effectiveness (WUE) and overall data center safety.

This paper focuses on two-phase immersion cooling, comparing various dielectric fluids in terms of their electrical properties, dissipation factors, material compatibility and the total cost of ownership, relative to other liquid cooling technologies.

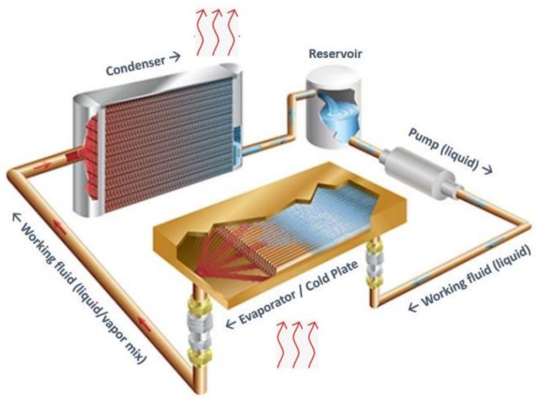

Figure 2: Schematic of the pumped two-phase direct to chip cooling operation [1]

2. PROPERTIES OF HEAT TRANSFER FLUIDS

Common dielectric fluids used in two-phase immersion cooling include perfluorocarbons (e.g., FC-72), hydrofluoroethers (e.g., HFE-7100), and fluoroketones (e.g., Novec™ 649). These fluids are selected based on several critical performance criteria, including non-flammability, boiling points within the 40–60 °C range, excellent dielectric properties at high frequencies, thermal stability, and chemical compatibility with a wide range of materials. From a heat transfer perspective, fluids with high latent heat of vaporization, thermal conductivity, and surface tension are preferred.

Table 1 summarizes some key thermodynamic and transport properties obtained through REFPROP, along with environmental characteristics of the established dielectric fluids and the newly evaluated Opteon™ 2P50. FC-72 has been widely used in two-phase immersion cooling, but its high global warming potential (GWP) poses significant regulatory challenges. HFE-7100 offers a lower GWP, but its relatively poor dielectric performance and higher normal boiling point of 61 °C may lead to elevated chip temperatures. Novec™ 649 presents a more balanced profile, with a GWP of just 1 and a favorable boiling point of 49 °C. However, its chemical stability can be compromised in the presence of contaminants such as moisture, necessitating stringent system design and control measures to ensure reliability [3]. Opteon™ 2P50 combines favorable thermal and dielectric properties with low GWP and high chemical stability, making it a strong candidate for two-phase immersion cooling applications [4].

Table 1: Thermophysical Properties and Environmental Characteristics of Two-phase Immersion Fluids [2]

Property	FC-72	HFE-7100	Novec™ 649	Opteon™ 2P50
Normal Boiling Point (ºC)	56	61	49	49
Liquid Density (kg/m^3)	1680	1520	1600	1456
Liquid Viscosity (cP)	0.64	0.58	0.64	0.62
Surface Tension (N/m)	0.010	0.014	0.011	0.011
Heat of Vaporization* (kJ/kg)	88	112	88	108
Liquid Thermal Conductivity (W/mK)	0.057	0.069	0.059	0.073
Liquid Specific Heat (kJ/kgK)	1.10	1.18	1.10	1.09
GWP	>5000	297	1	~10
ODP	0	0	0	0

*At normal boiling point

3. DIELECTRIC PROPERTIES AND SIGNAL INTEGRITY

Immersion cooling fluids come into direct contact with electrically active components such as servers, circuit boards, and power cables, so their dielectric properties are essential for ensuring both reliable system performance and electrical safety. These characteristics help maintain signal integrity and prevent unintended current flow.

Volume resistivity determines the fluid's ability to prevent electrical conduction. Opteon™ 2P50 exhibited a volume resistivity of 5.1×10^{14} Ω·cm (ASTM D1169), significantly exceeding the minimum requirement set by the Open Compute Project (OCP, 2022) [5]. Dielectric strength was further confirmed by breakdown voltage measurements: 41 kV across a 2.54 mm gap (ASTM D877) and 59 kV across a 2.5 mm gap (IEC 50156). These results demonstrate Opteon™ 2P50's excellent electrical insulating performance.

Table 2 presents a comparative analysis of the dielectric constant and dissipation factor for four dielectric fluids listed in Table 1, across frequencies relevant to high-speed data interfaces such as PCIe 5.0 (32 GHz). Opteon™ 2P50, FC-72, and Novec™ 649 exhibit dielectric constants below 1.8, meeting the Open Compute Project (OCP) requirement of <2.3. In contrast, HFE-7100 exceeds this threshold, with values above 3.0, rendering it unsuitable for such applications. Similarly, dissipation factor measurements reveal that Opteon™ 2P50, FC-72, and Novec™ 649 comply with the OCP limit of <0.05. Notably, Opteon™ 2P50 demonstrates superior performance, with dissipation factors approximately one order of magnitude lower than Novec™ 649 and maintaining values below 10^{-3}, indicating minimal dielectric loss at high frequencies.

Cable losses simulations were performed using CST Microwave Studio on a 1.0 (one) meter long 100 Ω Differential Cable for air, Opteon™ 2P50 and a fluid satisfying the minimum requirements of OCP ("OCP req."). The results listed in Table 3 show that Opteon™ 2P50 exhibits insertion loss nearly identical to that of air, indicating minimal impact on signal attenuation when air is replaced with the fluid. In contrast, the fluid "OCP_req," which meets the criteria outlined in Table 1, shows approximately twice the insertion loss of Opteon™ 2P50 at frequencies above 30 GHz.

Table 2: Dielectric constant (a) and dissipation factor (b) for different frequencies and fluids

(a)

	2.5 GHz	5.0 GHz	8.0 GHz	16 GHz	32 GHz
FC-72	1.66	1.66	1.66	1.66	1.66
HFE-7100	8.95	7.52	6.76	5.75	4.36
Novec™ 649	1.71	1.71	1.70	1.69	1.69
Opteon™ 2P50	1.74	1.74	1.74	1.74	1.74

(b)

	2.5 GHz	5.0 GHz	8.0 GHz	16 GHz	32 GHz
FC-72	$1.2\ 10^{-3}$	$1.3\ 10^{-3}$	$1.3\ 10^{-3}$	$1.3\ 10^{-3}$	$1.3\ 10^{-3}$
HFE-7100	$4.9\ 10^{-1}$	$5.1\ 10^{-1}$	$5.2\ 10^{-1}$	$5.3\ 10^{-1}$	$5.5\ 10^{-1}$
Novec™ 649	$8.5\ 10^{-3}$	$8.7\ 10^{-3}$	$8.8\ 10^{-3}$	$8.9\ 10^{-3}$	$9.0\ 10^{-3}$
Opteon™ 2P50	$7.7\ 10^{-4}$	$7.8\ 10^{-4}$	$7.8\ 10^{-4}$	$7.9\ 10^{-4}$	$7.9\ 10^{-4}$

Table 3: Cable insertion losses as a function of frequency

	2.5 GHz	5.0 GHz	8.0 GHz	16 GHz	32 GHz
Air	-1.27	-2.28	-3.46	-6.14	-10.3
OCP req. fluid	-1.94	-3.55	-5.82	-10.9	-19.7
Opteon™ 2P50	-1.30	-2.24	-3.56	-6.33	-10.6

4. MATERIAL COMPATIBILITY AND THERMAL STABILITY

Material compatibility with 2-PIC fluids is a critical consideration, as it directly affects component reliability, potential contamination, and the long-term integrity of materials exposed to the fluid during operation. The compatibility of several common materials used in servers and tanks were evaluated. Sealed tube tests were conducted on common plastic and elastomeric materials exposed to Opteon™ 2P50 at 80°C for two weeks. The weight change (%), volume change (%), and hardness change for the tested plastic materials are summarized in Table 4. The results indicated minimal interaction between the tested plastic and Opteon™ 2P50 during the exposure tests, confirming its suitability for use with most plastics. Certain elastomers and flexible materials may exhibit lower compatibility with 2-PIC fluids, primarily due to their high plasticizer content, which can be extracted by the fluid. Table 5 presents the material compatibility for Opteon™ 2P50 and common elastomers. Most materials showed very good compatibility, except for some fluorine-based materials such as FKM and Fluorosilicone which exhibited greater impact and whose use in 2-PIC systems should be evaluated on a case-by-case basis.

Table 4: Material Compatibility for Opteon™ 2P50 and Common Plastics

Plastic	Weight Change (%)	Volume Change (%)	Hardness Change
Nylon resin- Zytel® 330	-0.3	2.4	0.8
Nylon 6,6- Zytel® 101	-0.3	-0.1	0.1
Torlon® polymer	-0.3	0.0	<-0.1
Ryton® polymer	<-0.1	0.0	0.2
Teflon™	4.1	4.8	-1.1
HDPE	0.5	-0.9	-0.9
Polyurethane	-1.0	-0.3	1.6
Polypropylene	1.5	0.2	0.7
Polycarbonate	<-0.1	0.0	-0.5
PEEK	<-0.1	0.8	<-0.1
Bakelite	-0.7	0.8	1.0

Table 5: Material Compatibility for Opteon™ 2P50 and Common Elastomers

Elastomers	Weight Change (%)	Volume Change (%)	Hardness Change
Neoprene C1276 -70	-0.2	0.4	0
Neoprene C0873-70	0.2	0.0	0
Epichlorohydrin	-0.1	-0.2	-1
Butyl rubber	1.9	0.5	-3
EPDM	1.2	0.4	-2
Fluorosilicone	16.9	12.6	-15
HNBR nitrile	1.1	1.3	-2
NBR nitrile	<-0.1	3.3	0
Fluorocarbon FKM	14.0	16.3	-12
Natural Rubber	1.4	2.6	0
Silicone Rubber	4.3	3.3	-4

Sealed tube tests conducted according to ASHRAE 97-2007 (see Table 6), for 1 week at 175°C, revealed a clear contrast in the chemical stability between Opteon™ 2P50 and Novec™ 649. Novec™ 649 consistently produced elevated levels of fluoride and acidity, regardless of the presence of moisture and air, indicating that the fluid underwent decomposition under the test conditions. In contrast, Opteon™ 2P50 demonstrated superior stability, with both fluoride and acidity levels remaining below the detection limits—0.2 ppm for fluoride and 0.12 ppm equivalent HCl for acidity—even in the presence of moisture and air. These results suggest that Opteon™ 2P50 is more chemically robust and better suited for applications where long-term fluid integrity is critical.

Table 6: Sealed tube testing carried out at 175°C for 1 week, in the presence of Al, Cu, and carbon steel coupons. MDL is method of detection limit. (0.2 ppm for Fluoride and 0.12 ppm eq HCl)

		Test 1	Test 2
Test Conditions	Moisture (ppm)	0	20
	Air (mmHg)	0	48
Opteon™ 2P50 Results	Fluoride (ppm)	<MDL	<MDL
	Acidity (ppm eq HCl)	<MDL	<MDL
Novec™ 649 Results	Fluoride (ppm)	49.9	66.2
	Acidity (ppm eq HCl)	401	954

5. TOTAL COST OF OWNERSHIP (TCO)

A Total Cost of Ownership (TCO) analysis tool was developed to evaluate the overall cost and energy performance of various advanced data center cooling technologies including single-phase immersion (1-PIC), two-phase immersion cooling (2-PIC), and single-phase direct-to-chip (DTC)[6]. The model uses actual manufacturer performance data and basic engineering principles to calculate energy and water use for all energy consuming components such as fluid coolers, chillers, pumps, CRAH units and server fans. In addition to energy use, the operating expenses (OPEX) include maintenance costs. The capital expense (CAPEX) was obtained from actual cost of equipment from data centers and suppliers. The PUE (Power Usage Effectiveness) was annualized using calculated energy performance and meteorological data [7].

Using this model, a case study was conducted based on a standardized 36 MW data center configuration located near Washington, DC, United States, to compare two-phase immersion cooling, single-phase immersion cooling and single-phase direct-to-chip cooling. In this case study, outdoor heat rejection systems were designed using the location's 20-year climate extremes and manufacturer-rated cooling capacities. Regional electricity rates were also factored into the analysis. Some key assumptions are summarized in Table 7.

Table 7: Key Assumptions of the case study

Technology Options	Facility Supply Temp	Power per tank or rack
2-PIC	39°C	250kW
1-PIC	25°C	110kW
DTC (1P)	34°C	125kW

Figure 4 (a), (b), (c), and (d) show performance results in terms of space usage, annual power usage effectiveness, annual OPEX, and the 10-year total cost of ownership (US$ millions) for the various cooling technologies analyzed in the case study. It is noted that 2-PIC system can operate using either adiabatic fluids coolers or chillers to achieve the required facility supply temperature at this location. Among the cooling options analyzed in this study, 1-PIC system needs the largest building footprint due to its IT density. The yard space requirement for 2-PIC with adiabatic fluid coolers is larger, as it has a lower heat rejection capacity per unit area compared to chillers.

Two performance indices were used to present the annual power usage effectiveness (PUE) of each cooling technology. Cooling pPUE represents the partial PUE of the cooling equipment, while total PUE reflects the overall facility energy consumption required to operate the data center. As shown in Figure 4(b), 2-PIC shows lower values of PUE compared to 1-PIC and DTC. With the usage of adiabatic fluid coolers, 2-PIC yields the lowest cooling pPUE, which is 1.02.

Regarding the annual operating expense (OPEX) summarized in Figure 4(c), 2-PIC demonstrates operational cost benefits thanks to its lower PUE. Finally, the total cost of ownership over ten years of operation for each cooling technology is presented in Figure 4(d). 2-PIC with adiabatic coolers offers the most economical option due to its lower operating costs and competitive capital expenses, and its 10-year total cost of ownership is 14.3% and 13% lower than those of 1-PIC and DTC, respectively.

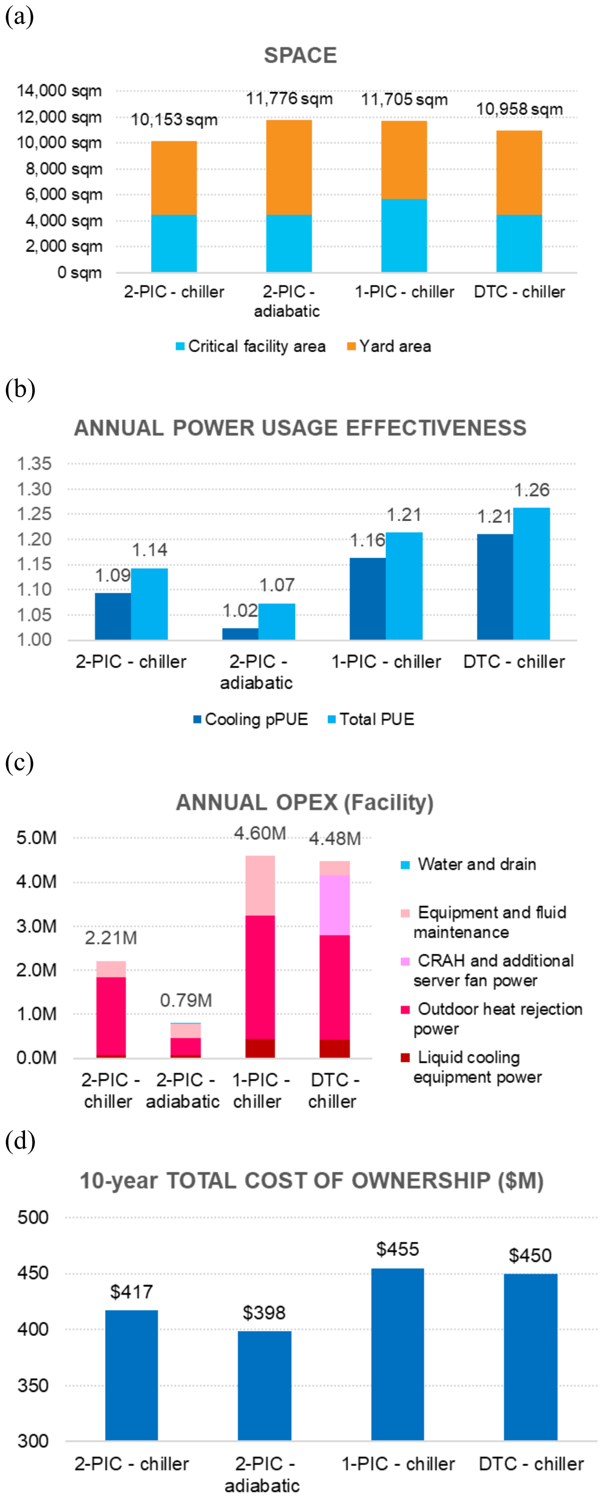

Figure 4: Case study of a 36MW data center: (a) space, (b) annual power usage effectiveness, (c) annual OPEX, and (d) 10-year total cost of ownership ($M).

6. SUMMARY

Thanks to its superior boiling heat transfer performance, two-phase immersion cooling (2-PIC) can significantly reduce energy and water consumption in data centers while supporting next-generation high-power chips. Opteon™ 2P50 offers a compelling combination of thermal efficiency, strong dielectric performance, low environmental impact, and high chemical resilience, positioning it as an excellent candidate fluid for 2-PIC systems. Its superior electrical insulation, low dielectric loss at high frequencies, and signal integrity comparable to air support operation in high-frequency electronic systems. Additionally, its excellent compatibility with common materials and outstanding thermal and chemical stability under elevated temperatures make it a robust choice for long-term deployment in data centers. Finally, a detailed Total Cost of Ownership (TCO) analysis for a 36 MW data center with various advanced data center cooling technologies including 1-PIC, 2-PIC, DTC was conducted. The case study results show that 2-PIC systems, particularly when using adiabatic fluid coolers, offer superior energy efficiency, lower operating costs, and competitive total cost of ownership, making them a highly effective cooling solution for large-scale data centers.

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