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Two-Phase vs Single-Phase Immersion Cooling Fluids: Deconstructing Myths with Science

May 2022

SUMMARY AND KEY TAKEAWAYS

There are many myths and misconceptions in the data center industry surrounding two-phase immersion cooling (2-PIC), particularly regarding fluid cost, safety, toxicity, sustainability and reliability.

Some of the negative perception around 2-PIC comes from a now obsolete, but frequently cited 2016 study by the Lawrence Berkeley National Laboratory (LBNL). The LBNL study was conducted with a fluid that had not been previously or sufficiently tested and validated for use with IT hardware. Since the early LBNL study, fluid material compatibility testing has evolved tremendously and approximately one thousand 2-PIC systems have been installed successfully around the world. In addition, new 2-PIC fluids with superior sustainability profiles and IT hardware compatibility are currently being evaluated by the industry.

This white paper tries to set the record straight while comparing two-phase immersion cooling and single-phase immersion cooling (1-PIC) across several categories:

Categories for Comparison

Safety

2-PIC uses fluorinated fluids which are volatile ("volatility" describes how easily a substance will turn into a gas or vapor), non-flammable and very safe to handle when used within the manufacturer's recommendations. Hydrocarbon-based oils typically used in 1-PIC are non-volatile but combustible, and can become a significant fire hazard.

Hardware Reliability

2-PIC relies on constant temperature phase change for heat removal which prevents temperature stratification found in 1-PIC tanks and keeps hardware cooler for greater longevity and reliability. Both 1-PIC and 2-PIC technologies require adequate contaminant controls and proper selection of cabling materials to minimize any hardware issues. Mechanisms of potential hardware failure in 2-PIC are preventable and well understood today.

Sustainability

2-PIC technology, when combined with new ultra-low Global Warming Potential (GWP) fluids, is the most sustainable cooling solution known today, providing the lowest CO2 equivalent emissions and overall energy consumption. .

Heat Removal Performance and Power Density

1-PIC is a great upgrade to air cooling but has limited heat transfer capabilities compared to 2-PIC. By taking advantage of phase change, 2-PIC provides 2 to 3 times more heat removal capacity than 1-PIC and enables significantly higher power density especially as more and more servers are designed around the technology.

System Complexity & Reliability

The absence of fluid pumps and Coolant Distribution Units (CDUs) make 2-PIC technology less complex than 1-PIC. Having fewer mechanical components in 2-PIC systems also reduces the number of potential failure points versus 1-PIC, providing superior overall reliability.

Operating Expenses and Upfront Costs

Although initial fluid costs and fluid loss expenses can be higher for 2-PIC, these are offset by lower cooling infrastructure and energy costs when compared to 1-PIC. Fluid costs can be further reduced by increasing IT power density.

Overclocking Enablement

A research paper published in 2022 by IEEE, CPU Overclocking: A Performance Assessment of Air, Cold Plates, and Two-Phase Immersion Cooling, has shown that 2-PIC can not only enable reliable overclocking, but improve sustainability, improve reliability, and reduce total cost of ownership.

2-PIC Fluids

Legacy 2-PIC fluids such as perfluorocarbons (PFCs), hydrofluoroethers (HFEs) and fluoroketones (FKs) have been safely and successfully used in 2-PIC systems. A new innovative family of fluids, called hydrofluoroolefins (HFOs), is also under evaluation.

INTRODUCTION

Data centers are used for everything from Artificial Intelligence to gaming, crypto-currency mining and solving complex algorithms. The harder data center servers work, the more heat they generate, and the more cooling is required.

In traditional data centers, this heat is removed by air cooling, which requires massive resources including high-capacity chillers, cooling towers and an enormous number of fans. Traditional air-cooled data centers also consume immense amounts of energy and water for cooling because of their low energy efficiency and the inherently poor heat removal capabilities of air.

For many years, the data center industry has been evaluating and deploying new cooling technologies. The most sustainable, energy efficient and cost effective of those is immersion cooling, where IT hardware is placed inside a tank and submerged in an electrically insulating liquid, called a dielectric fluid. Servers, chips and electrically charged components can be safely submerged in direct contact with a dielectric liquid and function normally.

Immersion cooling keeps IT hardware much cooler because dielectric fluids offer superior heat removal capabilities. More importantly, while air-cooled data centers typically use about 70% of IT power for cooling (as per ARPA-e DOE), with immersion technology this number can be as low as 2% while consuming little to no water. There are two basic methods of immersion cooling:

Single-phase immersion cooling (1-PIC), in which the dielectric fluid cools hot server parts by direct contact but remains in liquid phase while its temperature increases. Pumps are required to enable proper heat removal and to circulate the dielectric liquid to an external heat exchanger, where it is cooled and cycled back into the tank.

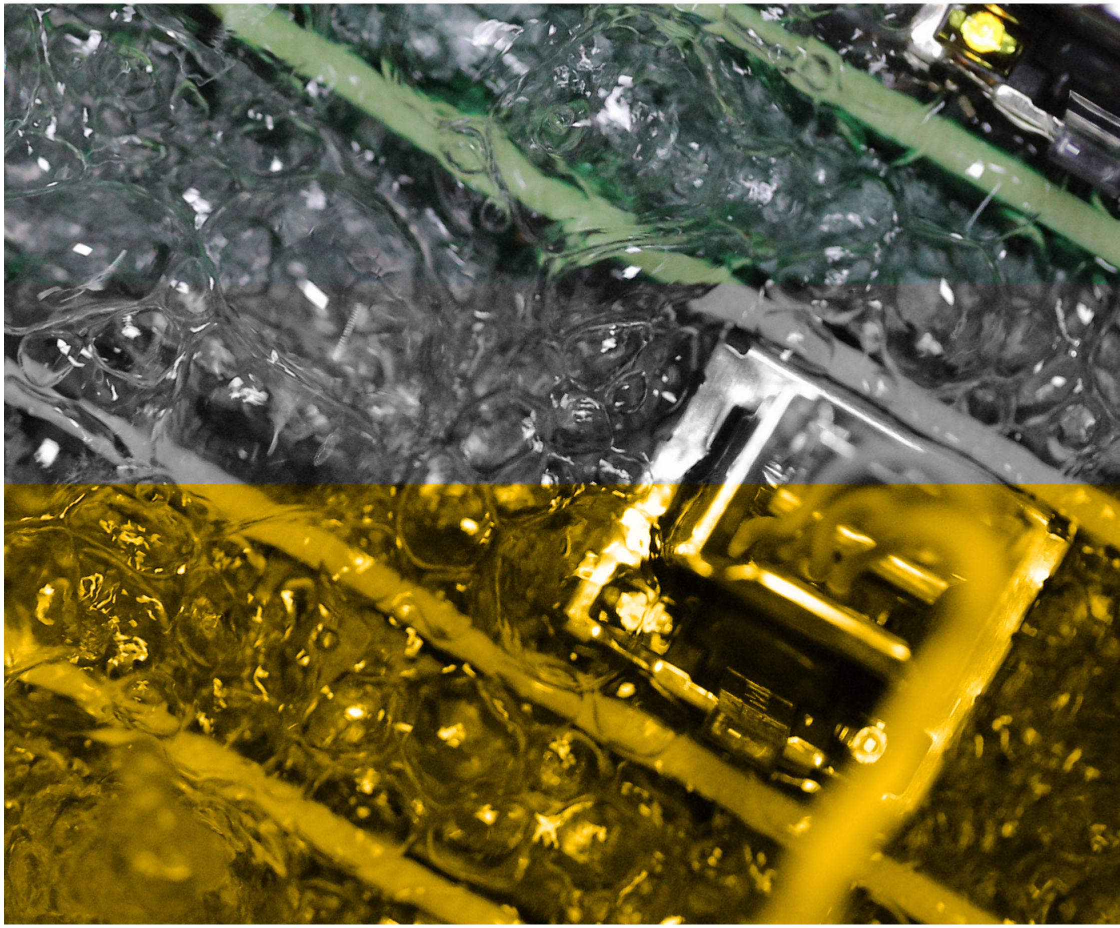
Two-phase immersion cooling (2-PIC), in which the dielectric liquid boils when in direct contact with hot server parts and turns into vapor. Vapor rises and condenses on a heat exchanger (condenser) above the surface, returning to a liquid state in a perpetual and passive cycle. Liquid temperature remains constant. There is no need for pumps for the cooling process – only a small auxiliary pump is used to circulate the fluid through a filter.

The logical question is: which one is the better immersion cooling technology?

There is plenty of debate within the data center industry around the pros and cons of 1-PIC and 2-PIC. With debate comes plenty of misinformation, which has been particularly focused on the safety, cost and sustainability aspects of the fluids used in 2-PIC. However, 2-PIC fluids are designed to be:

1. Safe to handle when used within the manufacturer's recommendations;
2. Non-flammable and non-combustible;
3. Non-ozone depleting – some have close to zero global warming potential (GWP);
4. Superior to single-phase liquids in terms of heat transfer and simplicity.

This white paper aims to provide a science-based discussion on the pros and cons of 1-PIC and 2-PIC technologies. It also addresses the major myths and misconceptions about 2-PIC fluids, and includes information that can be found in public records such as agency approvals and Material Safety Data Sheets (MSDS).



Immersion Fluids

1-PIC and 2-PIC use different types of fluids with unique properties and chemistry.

SINGLE-PHASE IMMERSION FLUIDS

Oils are typically used in 1-PIC because of their high boiling point and good thermal characteristics. Commonly used mineral oils are hydrocarbon- based and produced from fossil fuels. In addition, there are synthetic hydrocarbon (HC) oils such as poly-alphaolefins (PAO) which are produced through chemical reactions. While HC oils – synthetic or mineral – may be considered inherently biodegradable, they may not be readily biodegradable and are typically not bio-based. Depending on the source, HC oils may also contain sulfur, which can interact with, and even corrode, sensitive IT components.

HC oils have attributes such as good dielectric properties, low toxicity, and low fluid loss.

However, their high-viscosity "oily" nature can make for messy handling, lengthy maintenance of IT gear (degreasing) and can be difficult to pump or pour, particularly in lower temperatures. Oil can drip during maintenance and become a slip hazard, therefore rubber floor matting is required to reduce risks. Oil 'blooms' are also common with 1-PIC immersion cooling. This happens when oil residue accumu-lates on neighboring surfaces, typically within a 1 meter to 3 meter radius of the 1-PIC device. Another major concern with HC oils is flammability; HCs oils are combustible, have low flash points, and can become a significant fire hazard.

Fluorinated fluids – synthetic compounds con-taining fluorine – can also be used in 1-PIC. They typically have boiling points above 100°C, are non-flammable, and have lower viscosity than oils. However, 1-PIC fluorinated fluids may have less favorable thermal properties, such as lower liquid thermal conductivity. Some of them, including well-known PFPEs (perfluorinated polyethers) and PFCs (Perfluorocarbons), have very high Global Warming Potential (GWP), as much as 10,000.

TWO-PHASE IMMERSION FLUIDS

All dielectric liquids used in 2-PIC are fluorine- based and have lower boiling points (typically in the range of 40 to 60°C) than their 1-PIC counterparts in order to enable phase-change cooling.

2-PIC fluorinated fluids are often perceived as technologically sophisticated since they typically operate in closed systems not visible to the naked eye while water, glycols and oils routinely used in many cooling applications are more familiar to the average person. However, fluorinated fluids are just as common. They are safely used every day in air conditioning systems, household refrigerators, supermarket cabinets, cosmetics, inhalers, insulating foam – and many other places.

In addition to lower boiling points, fluorinated fluids have low viscosity, are non-flammable, have high chemical/thermal stability and are supplied with very high purity.

Their volatile nature means that in case of a spill, they will quickly evaporate, which has both pros (the server dries very quickly and is clean and ready for maintenance upon removal from the tank) and cons (potential greater fluid losses) related to immersion cooling. They can be subdivided into four groups, of which the first three are legacy fluids:

Perfluorocarbons (PFCs)

PFCs have been used for decades. They are non-flammable, chemically simple, compatible with most materials and have very good dielectric properties. However, well known PFCs such as FC-72 and FC-3284 have a very high GWP (~ 9000), so they come with elevated sustainability concerns.

Hydrofluoroethers (HFEs)

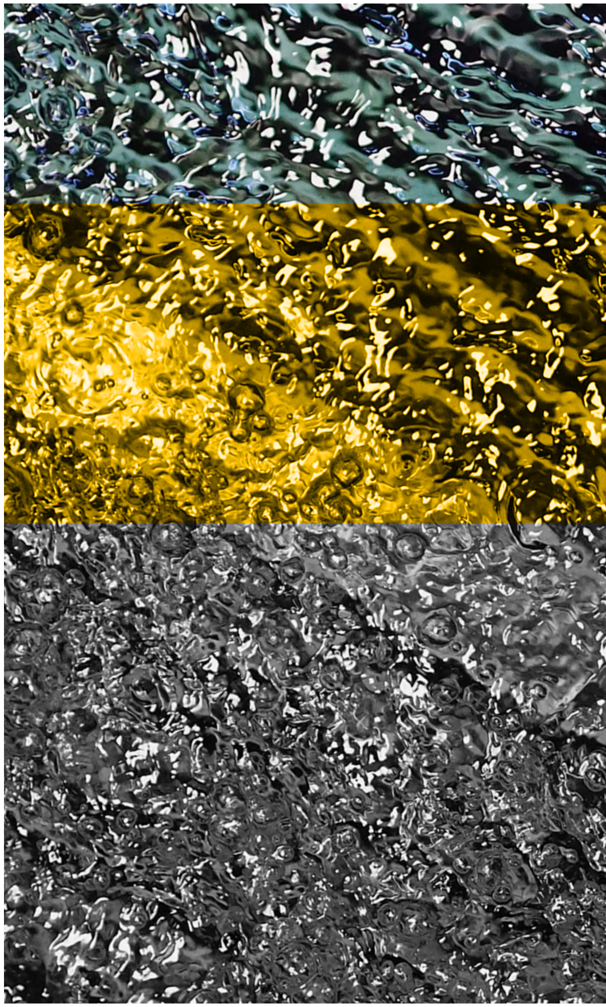
Also commonly used for electronic cooling, HFEs have good thermal properties and much lower GWP (around 300-500) than PFCs. HFEs are non-flammable, but do not have as good dielectric properties compared to PFCs, which leads to some application limitations.

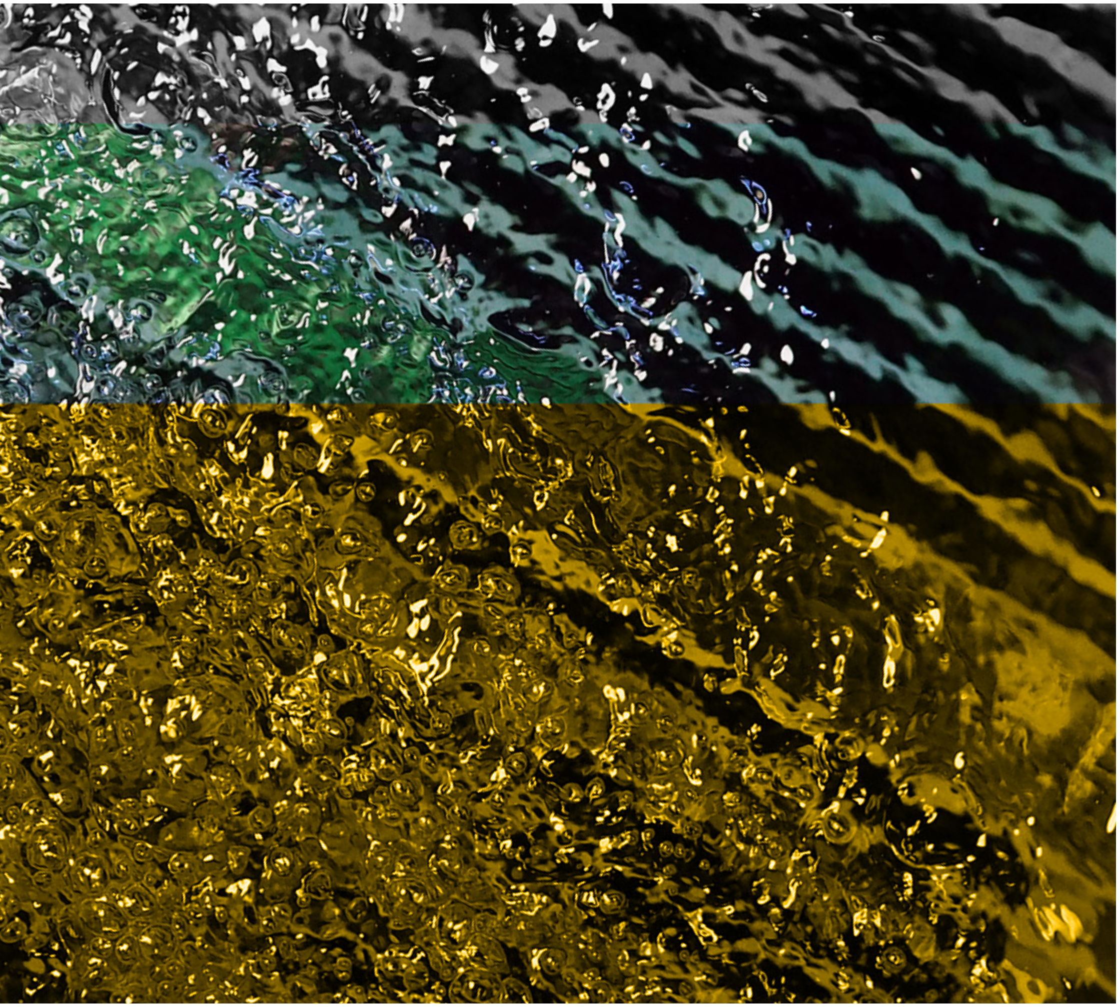
Fluoroketones (FKs)

FKs are also used in 2-PIC, particularly Novec 649, which is non-flammable, has better dielectric properties than HFEs, as well as an ultra-low GWP of about 1. However, when compared to other fluids, Novec 649 typically requires more stringent filtration and fluid hygiene to improve hardware reliability.

Hydrofluoroolefins (HFOs)

HFOs are a new innovative family of fluorinated fluids introduced in the last decade. They have ultra-low GWP and are considered long-term sustainable solutions in many applications such as air conditioning, foams, and personal care products. HFO dielectric coolants are now also under consideration for 2-PIC, with several evaluations by the industry underway. In addition to a very favorable sustainability profile, HFOs are typically non-flammable, have high chemical stability, excellent material compatibility and dielectric properties.





This paper will now focus on comparing 1-PIC and 2-PIC with particular focus on dielectric fluids. We will make every attempt to provide an objective analysis on the following topics:

1. Safety
2. Hardware Reliability and Fluid Aging
3. Sustainability
4. Heat Removal Performance and Power Density
5. System Complexity
6. Operating Expenses and Upfront Costs
7. Overclocking Enablement

Safety

Flammability

Flammability is a key concern when it comes to safety. HC-based oils are combustible and have low flash points. That means a flame or spark can cause the vapor above the liquid to ignite in the air. HC-based oils also have low fire points (the temperature above which a fluid can sustain a fire when ignited). The fire hazard of HC-based oils could impact risk assessments, increase complexity, installation costs, and hazard insurance premiums.

Fluorinated dielectric fluids, on the other hand, are considered non-flammable. The liquid has no flash point and the vapor is also non-flammable. In fact, some fluorinated dielectric fluids can act as flame suppressants and are commonly used in data centers for this purpose.

Toxicity

Another important safety category is toxicity. Any new chemical that is introduced to the market must go through rigorous toxicity testing in accordance with international protocols to identify and characterize its inherent hazards. Dielectric liquids accepted for commercial use also undergo a very thorough review process by government agencies. These comprehensive reviews consider both short and long-term exposure to humans and relevant environmental receptors; potential need for exposure mitigation controls such as personal protective equipment; ventilation/exhaust air; and emission control equipment and procedures. Derived health-based occupational exposure limits (OELs) are often communicated in Safety Data Sheets and/or technical guidance documents. Based on robust toxicology testing and risk assessments, 2-PIC fluids, when used according to their respective manufacturer's recommendations, have been demonstrated to be very safe for use in their respective applications.

2-PIC fluids will naturally have a higher concentration of vapors when the tank is opened for maintenance because of their higher vapor pressure. However, this vapor is considerably denser than air, so when the lid of a DataTank™ is opened, most of the vapor will stay within the tank unless agitated. Some tank manufacturers have also developed innovative technology to significantly reduce vapor loss (e.g. during installation or removal of IT gear) even if the dielectric fluid is agitated . When vapor is lost, the concentration around the tank can be further reduced with ventilation typical for conditioned spaces, namely with Make-up Air Units (MAUs). Since MAUs are required to meet human safety requirements in data center whitespace, no special equipment or ventilation is typically required to implement 2-PIC fluids for immersion cooling of IT equipment.

During normal operation with a closed lid and when the coolant is not pressurized (most commercial tanks operate at atmospheric pressure), fluid loss and vapor exposure are little to none.

Hardware Reliability and Fluid Aging

Fluorinated fluids are inherently more stable and have a longer life than HC oils due to the presence of fluorine. HC oils are also more sensitive to heat degradation and oxidation, which can generate a sludge if not properly maintained.

Hardware reliability depends on the chemical compatibility between fluid and server materials, as well as proper filtration and fluid hygiene. Both 1-PIC and 2-PIC fluids have their specific challenges related to material compatibility, which are well explained by the Open Compute Project annual reports on immersion cooling. Those issues should be addressed on a per fluid, per material basis while working closely with fluid, server, and tank manufacturers.

Both 1-PIC and 2-PIC systems need to maintain fluid hygiene to ensure hardware longevity and optimal performance. In 2-PIC systems, because the liquid dielectric is boiling, dissolved impurities can be deposited on hot surfaces by distillation. Filtering the liquid early in the system deployment can help ensure any dissolved impurities are removed and do not impact system performance. Therefore, in a 2-PIC system, the filter element is often replaced after the first 1-2 weeks of operation (following start-up) to ensure proper operation and predictable outcomes. Usually, the performance impact on a system without proper filtration is limited to distillation of impurities on boiling surfaces, which can be reversed by introducing new filters to clean the liquid.

Both types of immersion cooling improve hardware reliability because the server boards are fully submerged and temperature controlled. The tanks also keep out dust, particulates and contaminants that are otherwise prevalent in air cooled data centers. In a 1-PIC or 2-PIC system, the server fans are removed which reduces moving parts and minimizes failure points. Due to the superior heat removal capabilities and thermal stability of 2-PIC versus 1-PIC however, IT hardware operates much cooler which further improves its reliability and longevity.

Sustainability

When it comes to sustainability, a number of critical factors must be considered, such as CO_2 emissions, energy consumption, fluid losses and water use, among others.

CO_2 EQUIVALENT EMISSIONS

CO_2 emissions associated with cooling a data center are mostly a result of:

Energy consumption

When energy is generated by fossil fuel power plants, CO_2 is released to the atmosphere. The higher the data center energy consumption, the higher its CO_2 emissions. Data centers that use more energy from fossil fuel power plants and less from renewables will generate more CO_2. Both 1-PIC and 2-PIC have very low PUEs (Power Usage Effectiveness) compared to air cooling, which means the amount of energy used for cooling the servers is very small – typically 2% to 8% of the total IT power. 2-PIC offers slightly better partial PUE (1.02 to 1.04) when compared to 1-PIC (1.05 to 1.07).

In addition, immersion cooling lowers CO_2 emissions by reducing material consumption for IT hardware and electrical, cooling and building infrastructure.

Fluid losses

2-PIC fluids are volatile by nature and can be accidentally released into the atmosphere. The higher the fluid GWP – the measure of how many times the fluid is a more powerful greenhouse gas than CO_2 – the higher its CO_2 equivalent emissions. Fluid losses typically occur during server maintenance or because of ongoing leaks through poorly designed or manufactured tanks. Checking and keeping the seals in good condition and ensuring the lid is locked will significantly reduce fluid loss. During maintenance, the lid should be kept closed whenever possible. With good practices, annual 2-PIC fluid losses can be lower than 2%, which will result in lower CO_2 equivalent emissions and operating costs.

2-PIC fluorinated fluids can also be reclaimed and eventually re-used with few losses. Reclaim-and-recycle is fairly common in the refrigeration and air conditioning industry. It is more environmentally friendly and can reduce the cost of replenishing the fluid. LiquidStack has also developed fluid cleaning systems which can restore reclaimed fluid to a state that approaches virgin condition.

In 1-PIC, although HC oils could be recycled at end of life, re-refining for reuse may not be economical, and wasted HC oils may end up being incinerated, generating CO_2 emissions.

TOTAL CO_2 EMISSIONS ESTIMATES

Here we carry out an exercise of estimating the total lifetime CO2 equivalent emissions for different data center cooling technologies (Table 1). Three sources of emissions are included: cooling energy emissions, ongoing fluid losses and end-of-life fluid emissions.

TABLE 1 – TOTAL LIFETIME CO_2 EMISSIONS

	Today's Air Cooling	1-PIC	2-PIC		
		HC Oil	PFC	HFE	HFOs / FKs
PUE (Typical/Average in the US)*	1.57	1.06	1.03	1.03	1.03
Maximum GWP of fluid and refrigerants	1,924	<10	9,000	300	<10
Average Cooling Annual Energy Consumption for a 10MW Data center [GWh]	25	2.6	1.3	1.3	1.3
CO_2 Emissions due to Cooling Energy Use at 0.42 kg CO_2/kWh [Tons of CO_2]	10,500	1,100	550	550	550
Annual CO_2 Emissions due to fluid losses, 2%/year [Tons of CO_2]	400	0	14,250	450	15
Annual CO_2 Emissions due to fluid losses and cooling energy [Tons of CO_2]	10,900	1,100	14,800	1,000	565
15-year CO_2 Emissions [kTons of CO_2]	163	17	222	15	8.5
End of Life emissions at 20% loss of fluid [Tons of CO_2]	4	0**	135	5	0.2
15-year total Emissions [kTons of CO_2]	167	17	357	20	8.7

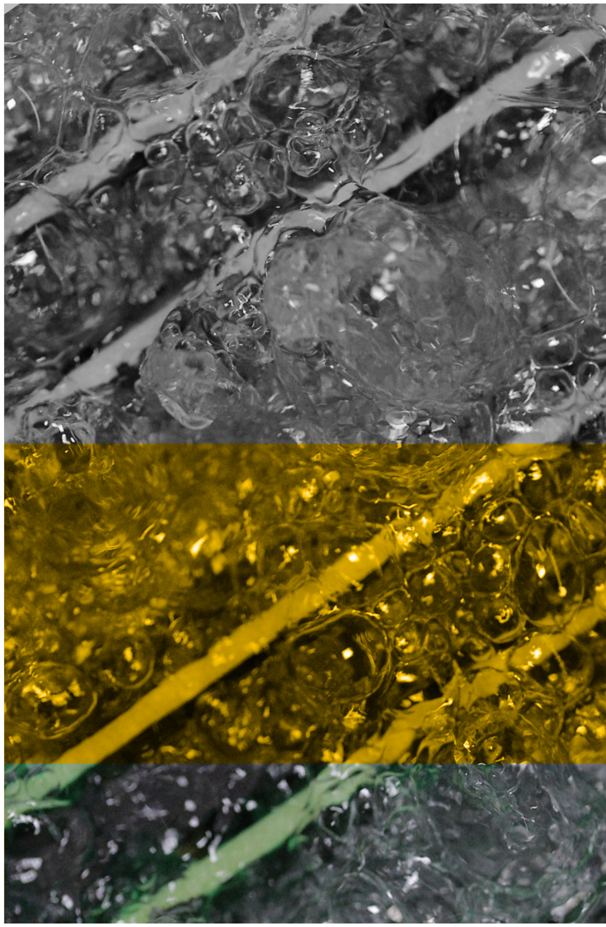
* Uptime Institute, 2021
** Potential emissions from oil loss or oil disposition at end of life were not taken into account

KEY TAKEAWAYS

- 1-PIC with HC oil leads to a significant reduction in CO_2 emissions versus air cooling even though potential emissions from oil loss or oil disposition at end of life were not taken into account;
- With lower GWP fluids such as an HFE, 2-PIC has very low total CO_2 emissions, similar to 1-PIC;
- Finally, ultra-low GWP fluids such as HFOs and FKs can lead to the lowest total CO_2 emissions.

WATER CONSUMPTION, PHYSICAL FOOTPRINT AND POTENTIAL FOR WASTE HEAT RECOVERY

Both 1-PIC and 2-PIC technologies are well known for low water consumption compared to air cooling. Immersion cooling systems typically leverage much higher water temperatures to cool or condense the dielectric coolant, which means heat can be rejected to high outside ambient temperatures with very little to no evaporative cooling, or can be recovered for other purposes. 2-PIC can operate at even higher water temperatures than 1-PIC, thus reducing the use of water to zero in most geographical locations as well as increasing the energy efficiency and reducing the physical size of waste heat recovery systems. Both 1-PIC and 2-PIC data centers are also known for having much smaller physical footprints. However, 2-PIC immersion cooling can reduce whitespace requirements by as much as 69% and data center site plots by up to 61% due to superior fluid thermal properties and higher compute density. According to a 2022 case study by Page, 2-PIC can reduce physical footprint per kW of power by at least another 20% compared to 1-PIC.



Heat Removal Performance and Power Density

2-PIC has several advantages in heat removal over 1-PIC.

a. The heat transfer performance in 2-PIC is at least 10-20 times higher than that of 1-PIC. As a result, more heat can be removed in the same CPU / GPU footprint, and chips will have far lower junction temperature.

b. To offset lower heat transfer performance of single-phase fluids, bulky extended surfaces, such as heat sinks, may have to be attached to CPUs and GPUs limiting compaction. For pool boiling, low-profile compact boiler plates and boiling enhancement coatings(BEC) can be used. Typical BECs are approximately 1mm in height. Together with the required removal of the IT equipment fans, this allows for up to an 84% reduction in IT server size by volume when leveraging 2-PIC immersion cooling.

c. In 2-PIC, the hotter the IT component becomes or the more heat that is rejected, the higher the heat transfer performance. In other words, two-phase heat transfer by boiling is naturally more effective when it is needed most. Boiling of 2-PIC fluids is only constrained at very high heat rejection values. In contrast, single-phase fluids need a significant increase in pump flow or lower coolant temperature in order to meet cooling demands.

d. Another concern with 1-PIC is temperature stratification inside the tank—i.e., some parts of the server and the tank will become hotter than others. With two-phase systems, the fluid boils at a constant temperature, so all liquid inside the tank has a uniform temperature.

Although power density values for 1-PIC and 2-PIC racks are much higher than air-cooled racks, two-phase immersion has the potential to double or even triple the heat rejection (IT power density) versus single-phase as more IT, storage and networking hardware is designed around the technology. 2-PIC also allows for much greater server design flexibility due to uniform fluid temperatures in the tank.

System Complexity

Two-phase systems are not more complex than their single-phase counterparts. They simply have a few differences:

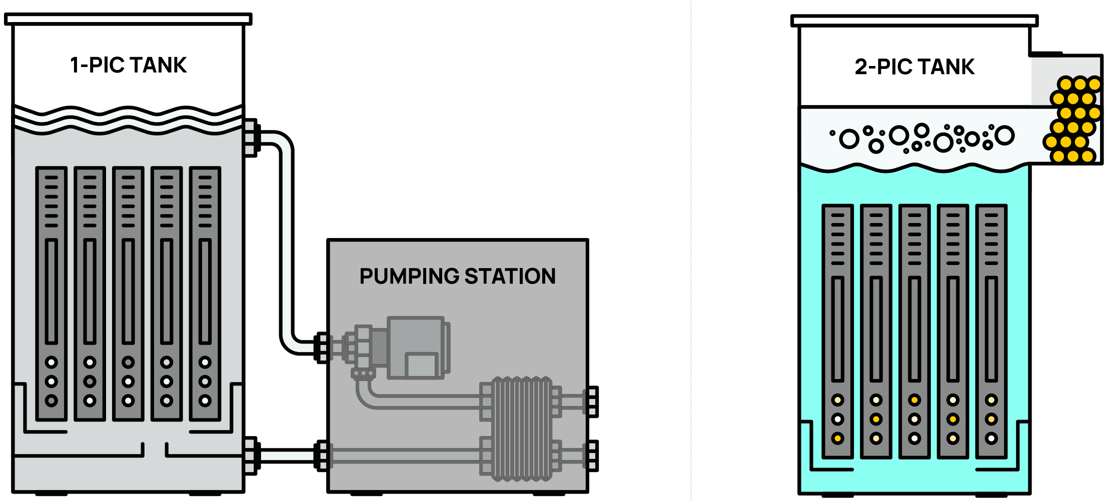
a. 1-PIC systems require a pump (or pumps) to circulate the dielectric fluid. In the event of pump(s) failure, the system must rely on natural convection, and server temperatures can quickly rise. 1-PIC heat removal is therefore more complex than 2-PIC as the 1-PIC systems must be carefully designed to ensure that a fresh supply of dielectric fluid is constantly pumped to the heat generating IT components.

b. 2-PIC systems are passive – they don't require a pump to remove heat. The liquid boils, the vapor naturally rises, and then it condenses back to liquid when in contact with condenser tubes positioned in the vapor zone.

A properly built 2-PIC system uses a vapor management system to retain fluid inside the tank to keep annual leak rate below 2%.

Both 1-PIC and 2-PIC need filtration systems as well as heat exchangers to cool or condense the dielectric fluid.

1-PIC VS 2-PIC



Operating Expenses and Upfront Costs

Operating expenses are driven by typical mechanical and general maintenance, fluid replacement and energy costs. For 2-PIC, fluid replacement costs represent less than 5% of the annual maintenance costs, which are offset by its lower energy costs (higher energy efficiency compared to single phase). As discussed, good practices and high-quality tanks can further reduce fluid loss expenses. It is important to mention that the fluid losses reported by the 2016 LBNL study – above 10% – do not reflect the current state of the 2-PIC technology, which is typically less than 2% per year.

A common concern of 2-PIC relates to upfront CAPEX due to higher fluid costs compared with HC oils. While this is true, independent case studies show that higher initial 2-PIC fluid costs are offset by lower piping, pump and cooling infrastructure costs when compared to 1-PIC.

Fluid costs can be reduced by taking advantage of the space-saving benefit of 2-PIC, allowing much higher power density per Rack Unit space versus air cooling, conductive cooling (cold plates), and 1-PIC cooling. This means server OEMs and integrators are no longer limited to traditional "U" space and can transform it from 'mostly air' to mostly hardware. Bulky heat sinks can be removed and server layouts can be optimized to place boards very close to each other, with as little as 2.5mm pitch, thus drastically reducing fluid volume.

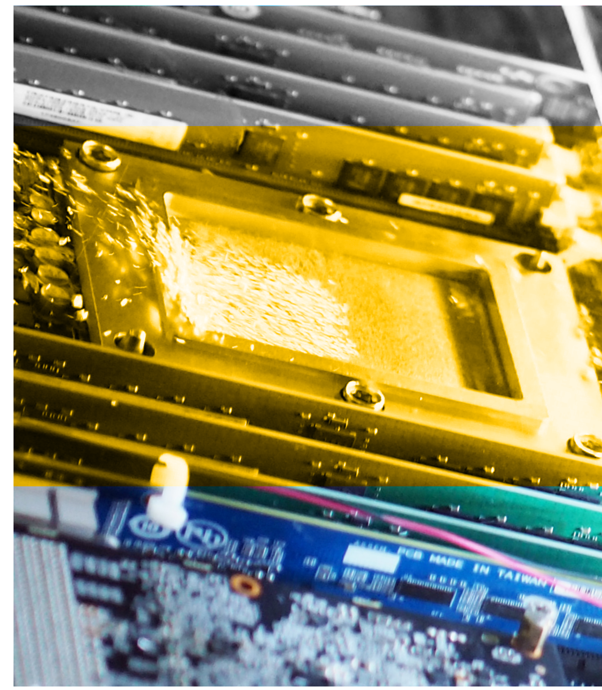
For example, in a scenario where 2-PIC fluid costs four times more per gallon than 1-PIC, but enables four times more power density, the total fluid cost per kW would be the same.

Furthermore, overclocking capabilities and better containment of fluid evaporation losses also tilt the scale in favor of 2-PIC.

Overclocking Enablement

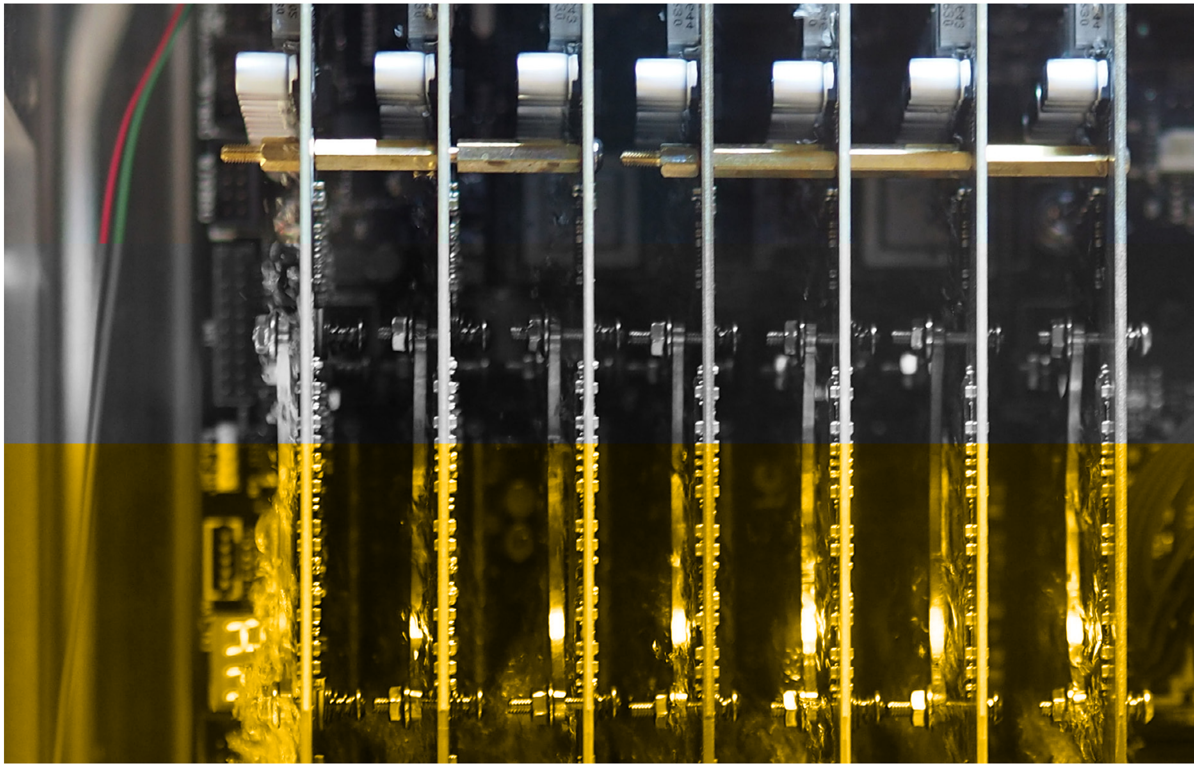
Microsoft's Zissou recently published the results of a comprehensive study exploring 2-PIC technology and how it enables overclocking without adversely affecting the hardware performance or lifespan. Zissou's research argues that 2-PIC has significant advantages over 1-PIC, Direct-to-Chip (cold plates) and other liquid cooling methods. Here a few highlights of Zissou's research:

- While overclocking increases power consumption substantially, immersion cooling provides power savings that offset higher energy requirements.
- 2-PIC can compensate for degradation caused by overclocking. When overclocking with 2-PIC, the server lifetime equals that of an air-cooled server with no overclocking.
- Added costs such as 2-PIC tanks and fluid are offset by lower data center PUE, which enables use of the reclaimed power towards adding more servers and thereby amortizing all costs (construction, energy, IT, operations) across more cores.
- Overclockable 2-PIC data centers reduce TCO by 4% when compared to the non-overclockable air-cooled datacenter.



CONCLUSION

2-phase immersion cooling technology has a very favorable environmental, health and safety profile while using fluids that are low-toxicity, non-flammable, non-corrosive and can have a very low GWP. These fluids offer wide operating temperature ranges, have excellent compatibility with most materials and are simple to maintain. And they do all this while significantly increasing power density, enabling overclocking and reducing CAPEX, OPEX and TCO. This makes two-phase immersion cooling a superior alternative to air, water or 1-PIC systems.



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