Evaluating immersion cooling fluids for data centers: a comparative study between hydrocarbon oils and fluorinated fluids

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Abstract:

As the computational demands on data centers continue to increase, efficient and sustainable cooling solutions are becoming critical. Traditional air-cooling systems are getting overwhelmed particularly in high-density server environments, due to their high energy consumption and limited heat dissipation capacity. Immersion cooling, which submerges electronic components in dielectric fluids to manage heat, has emerged as a promising alternative. This paper evaluates the performance, safety, and compatibility of three immersion cooling fluids, a hydrocarbon oil, Thermasolv™ CF2 (a fluorinated single-phase fluid), and Thermasolv™ IM6 (a fluorinated two-phase fluid). Three parameters: the cooling efficiency, material compatibility, and safety profiles of the fluids were assessed. The results demonstrate that both Thermasolv™ CF2 and IM6 outperform hydrocarbon oil in terms of heat dissipation, with IM6 showing the highest cooling efficiency due to its two-phase nature. Additionally, the Thermasolv™ fluids exhibit superior material compatibility and safety, with no flashpoint and non-toxic properties, compared to the potentially hazardous hydrocarbon oil. The findings highlight the advantages of using fluorinated fluids for immersion cooling in data centers, particularly in enhancing cooling performances, reducing energy consumption, and improving safety. This study provides valuable insights for selecting optimal cooling solutions in next-generation high-density data centers.

Key words: Immersion cooling, single-phase immersion, two-phase immersion, fluorinated fluid, hydrocarbon oil

Introduction

As the demand for computational power grows, driven by advancements in AI, crypto mining, and cloud computing, data centers face increasing challenges related to heat dissipation and energy consumption. Currently, data centers are estimated to consume about 1 to 1.5% of global electricity [1], with cooling systems alone accounting for up to 40% of this energy consumption [2]. As modern hardware becomes increasingly powerful and densely packed, traditional air-cooling systems are struggling to keep up with the rising thermal loads, resulting in higher energy costs and operational inefficiencies. That's why it is a necessity to have more advanced, energy-efficient cooling solutions to support this exponentially growing demand for computational power without neglecting the environmental impact. Immersion cooling is an emerging technique that consists in submerging electronic components directly in a thermally conductive but electrically insulating fluid. This promising technique has brought attention and many discussions are rising, and people are considering it as a compelling alternative. By directly absorbing heat into a liquid, immersion cooling can achieve significantly lower energy usage compared to air cooling. Studies suggest that advanced immersion cooling setups can bring Power Usage Effectiveness (PUE) down to as low as 1.03 on average, whereas with air-cooling the average PUE is between 1.5 and 1.7, allowing for nearly all consumed energy to go directly to computing rather than cooling [3].

Beyond energy efficiency, immersion cooling offers additional benefits critical to the future of data center design. The increasing number of data centers that are still using air-cooling as a cooling technique, takes a lot of space whereas immersion cooling enables greater server density and provides a stable, uniform thermal environment, which can also extend hardware longevity. These characteristics are essential for scaling up high-density data centers as demands increase, helping operators avoid the need for costly expansions and extensive cooling infrastructure.

Immersion cooling being the best choice, some questions remain: which one is better between single-phase and two-phase immersion? Which type of fluid should be chosen, hydrocarbon oils (which are the most commonly used in single-phase immersion) or fluorinated fluids, which could be used both for single and two-phase immersion cooling?

The aim of this paper is to provide a comparison between three types of fluids for immersion cooling: a hydrocarbon oil and two fluorinated fluids from Inventec: Thermasolv™ CF2 for single-phase and Thermasolv™ IM6 for two-phase. the safety of all fluids, their compatibility and of course their performances will be assessed. This paper is a more in-depth analysis that has been done during a webinar at the Spring summit Thermal Live called: Thermasolv™ Fluorinated Fluids vs Hydrocarbons for Immersion Cooling [5].

Experimental Methodology

There are two types of immersion cooling technique, either single-phase immersion or two-phase immersion. Single-phase immersion consists of fully submerging the server into a dielectric fluid that will cool it by direct contact. This technique needs high boiling point fluids to remain in the liquid state since the fluid's temperature will rise while dissipating the heat from the server. Also, a pump is required to circulate the fluid to a heat exchanger where it will be cooled down and then cycled back to the tank to enable proper heat removal. Fig.1 shows a schematic diagram of a single-phase system.

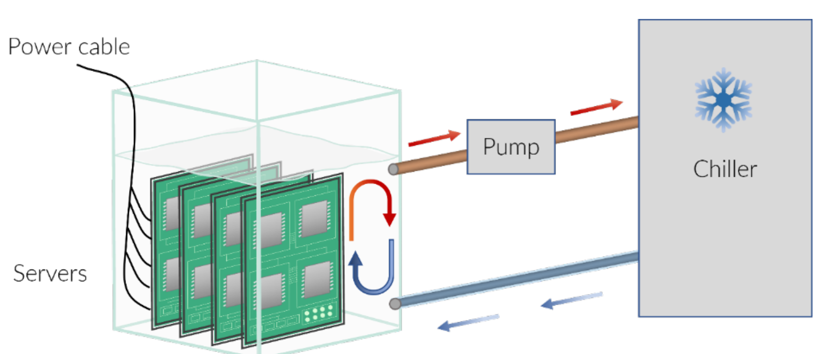


Figure 1. Schematic diagram of single-phase immersion cooling system

The second type of immersion cooling is two-phase immersion. Like single-phase immersion, two-phase immersion cooling requires the servers to be fully submerged in a dielectric but thermally conductive fluid to dissipate the heat generated by them. However, the difference lies in the type of fluid used. For two-phase immersion, the fluid needs to have a low boiling point, that way, as the server generates lots of heat, the fluid, which is in direct contact with the server, will start boiling and thus turn into vapor. The vapor will rise and meet a condenser at the top of the tank and will condense, making them return to a liquid state perpetually. Thanks to this cycling process, there is no need for any pump when using two-phase immersion cooling, which means that it can lower the energy consumption even further. Fig. 2 shows a schematic diagram of a two-phase immersion system.

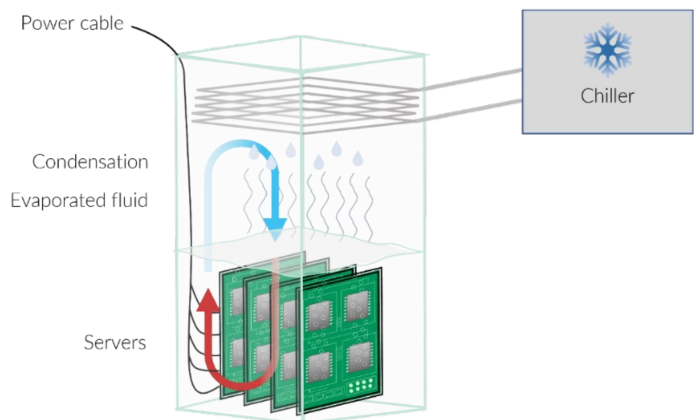


Figure 2. Schematic diagram of a two-phase immersion cooling system

The server is fully immersed in the cooling fluid; therefore, the fluid needs to have dielectric properties. three different fluids have been chosen to compare to each other: a hydrocarbon and two fluorinated fluids from Inventec Performance Chemicals, the Thermasolv™ CF2 and the Thermasolv™ IM6. Their properties are given in the table below.

Table 1: Dielectric fluids' properties

Dielectric fluid	Hydrocarbon fluid	Thermasolv™ CF2	Thermasolv™ IM6
Flash point (°C)	200	No flash point	No flash point
Boiling point (°C)	285	110	47
Density at 20°C (kg/m^3)	806	1815	1600
Kinematic viscosity at 40°C(mm^2/s)	9.8	1.35	0.36
Specific heat at 20°C (J/Kg.K)	2274	1087	1044
Thermal conductivity at 40° (W/m.K)	0.142	0.112	0.105

Compatibility assessment

Before assessing the cooling performances of the different fluids, it is also essential to run compatibility tests to see whether or not the cooling fluids would react with the different materials that are more likely to be in a server. The compatibility test is carried out to measure the ability of each fluid to extract non-volatile materials that would be in the sample which would mean that the sample is being damaged by the liquid. Nine different elastomers among the most encountered ones according to OCP (Open Compute Project) [4] have been chosen:

- EPDM
- Viton
- PTFE
- Nitrile
- Polyurethane
- Silicone rubber
- Natural rubber
- Chloroprene
- PVC

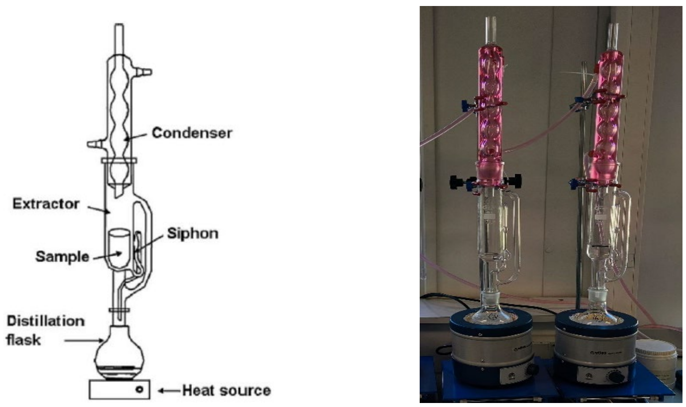
First of all, we take a sample of each elastomer that we weigh before and after the extraction. The mass change in percentage is expressed as follows:

$$\Delta w = \frac{wf - wi}{wi} \times 100$$

Where w_f is the final weight and w_i is the initial weight.

Since the fluids tested are either used for single phase immersion or two-phase immersion cooling, the compatibility assessment method isn't the same. For single phase immersion fluids, a vial is filled with the fluid to test, and the sample is added into it. Then the vial is put in an oven at 100°C for fourteen days.

For two-phase immersion fluids the test is different, we perform a Soxhlet extraction for 48 hours which is more suitable since the fluid will be tested at its boiling temperature. For both tests we consider that the fluid is compatible with the material tested if $\Delta w < 15\%$



(a) (b)

Figure 3. (a) Schematic image of a Soxhlet, (b) Photo of the Soxhlet experimental setup

Safety assessment

Another important thing to evaluate is the safety of the fluids. One of the key parameters regarding the fluids' safety is the flammability. To assess it we pour a little bit of each sample to test in an aluminum foil weighing vessel and then we bring a flame close to it to see whether the fluid catches fire or not.

Performance assessment

Last evaluation which is probably the most useful one to compare different cooling fluids together is their performances i.e. their ability to dissipate the heat.

Before using a server to assess the performances of the different dielectric fluids we decided to use a ceramic heat source to evaluate the ability of each fluid to dissipate the heat.

Then a server was used with the following components with a total power of 316 W:

- i5 quad core processor from Intel at 3.3GHz
- GeForce GTX 460 SE GPU from Nvidia

Both the heat source and the server were immersed in a 56L stainless steel tank filled with 10 to 15 L of dielectric fluid.

The first test consisted of immersing a heat source made of ceramic that could heat up to 200°C in the open air, in a tank filled with 10L of either the hydrocarbon oil, the Thermasolv™ CF2 or the Thermasolv™ IM6. For this experiment, thermocouples were used to record 3 different temperatures: One was placed at the heat source's surface to record its temperature while the other two were placed in the bath to record the fluid's temperature at the tank inlet and outlet. The thermocouples used are the Thermo Button 22T from Proges Plus, allowing to record temperatures from 0° to 125° at specified intervals with an accuracy of ±0,5°C. For the hydrocarbon oil and CF2 assessments, the pump used is a 230V AC voltage from Flojet with a maximum flow rate of 6L/min with a Viton membrane. Its dimensions are (LxHxW) 204x 101 x 92 mm^3. Using a pump produces forced convection, allowing a better flow distribution and thus a more homogeneous bath translating into a better heat dissipation.

The heat source was immersed for 2 hours and temperatures were recorded every five minutes. After two hours the temperature sensors were withdrawn, and the data were collected.

After assessing all three cooling fluids with the simple heat source, the next step was to work under real conditions with a running server to see how each fluid would compare to each other but also if the results we would get, would be similar to the ones from the previous experiment. The experiment is quite similar to the first one, a server is used this time instead of a ceramic heat source and we immerse it in the same tank but filled with 15L of each product which is the necessary volume to fully immerse the server.

For the server testing we used a software called Heavyload in order to stress our CPU to its maximum limit. The more stressed the CPU, the more heat it will generate. Having the CPU working at 100% of its capacity would translate the worst-case scenario that could occur with a server which is a good way to assess the cooling fluids' performances. Heavyload is also able to stress the GPU or the RAM or even the disk space or all four parameters together, however we only decided to stress the CPU for our tests. To stress the CPU to its limit, the software is continuously performing complex calculations to stimulate the load of the processor.

Contrary to the first tests carried out on the ceramic heat source, the CPU temperature wasn't recorded thanks to thermocouples but instead with a software called CoreTemp. CoreTemp is a program that is able to record the CPU temperature by showing the temperature on each core in real time. The software takes all the data from a Digital Thermal Sensor or DTS that is located near the hottest part of each core. CoreTemp can access these data and thus can provide a reliable and accurate temperature reading. Two thermocouples were still used to record the inlet and outlet temperature. The server was immersed for two hours, and the temperature was recorded every ten minutes. We also ran the server at open air with the same stress applied to the CPU thanks to HeavyLoad, to see how a server cooled only with air thanks to the fans would compare to a server cooled using immersion cooling.

Results

Compatibility assessment

Table 2 shows the compatibility results between the three fluids tested and the nine selected elastomers for trials. The values highlighted in red are the ones above 15% mass variation which translates an incompatibility between the fluid and the material. The value in yellow is close to 15% and therefore almost incompatible. The hydrocarbon oil tested is heavily incompatible with three materials: EPDM with a 63.2% mass variation, natural rubber with a 127% mass variation and PVC with a 49.6% mass variation. Silicon rubber is almost incompatible too with a 14.6% mass variation. In comparison, both Thermasolv™ CF2 and IM6 show similar results with a great overall compatibility with most elastomers tested. PVC is the only material incompatible with both of them with a 33.4% mass variation for CF2 and 19.4% for IM6.

Table 2. Material compatibility comparison between hydrocarbon oil, CF2 and IM6

Material	Hydrocarbon oil	Thermasolv™CF2	Thermasolv™ IM6
EPDM	**+63.2%**	**-3.1%**	**-0.4%**
Viton	**-0.4%**	**+8.4%**	**+1.8%**
PTFE	**0%**	**+5.9%**	**+4.4%**
Nitrile	**-6.8%**	**-5.8%**	**-1.0%**
Polyurethane	**+0.8%**	**0%**	**+0.4%**
Silicone rubber	**+14.6%**	**+3.5%**	**-1.6%**
Natural rubber	**+127.0%**	**+0.9%**	**-0.8%**
Chloroprene	**-2.7%**	**-4.9%**	**-2.7%**
PVC	**-49.6%**	**-33.4%**	**-19.4%**

Safety assessment

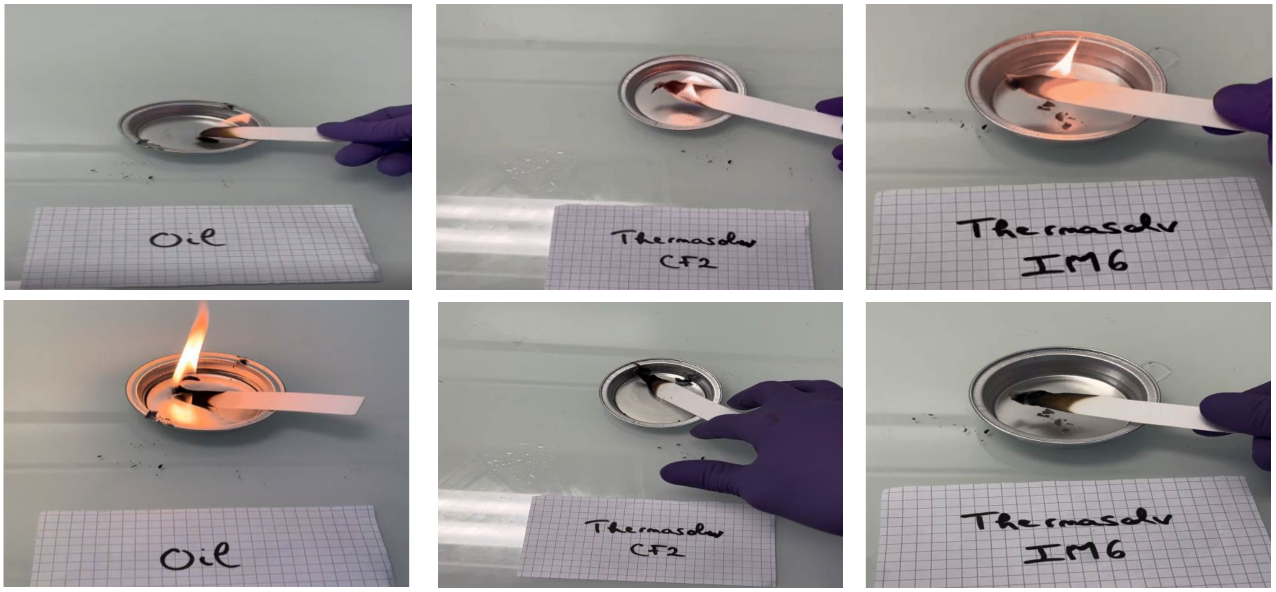
Next key parameter to assess to compare the fluids to each other is safety. It is indeed essential to have the safest fluid possible to avoid any issue either with the server or with the operator. Table 3 shows a few properties of the different fluids regarding safety:

Table 3. EHS properties of the dielectric fluids

Dielectric fluid	Hydrocarbon oil	Thermasolv™ CF2	Thermasolv™ IM6
Toxicity	H304	No hazard statement	No hazard statement
GWP	0	<120	1
Flash point (°C)	200	No flash point	No flash point
Viscosity at 40°C (mm^2/s)	9.8	1.35	0.36

Both Thermasolv™ CF2 and IM6 don't have any pictogram and aren't toxic compared to the hydrocarbon that is potentially harmful to the operator. However, all three cooling fluids have very low environmental impact regarding GWP according to the last IPCC report [6]. Another parameter that is meaningful regarding safety is viscosity. CF2 and IM6 have a very low viscosity compared to the hydrocarbon. This high viscosity added to the oily nature of the fluid can make it hard to handle during maintenance which could lead to slip hazard if spilled on the floor.

We then tried to assess the flammability of all fluids. Fig. 4 shows the flammability test on (a) hydrocarbon fluid, (b) CF2 and (c) IM6



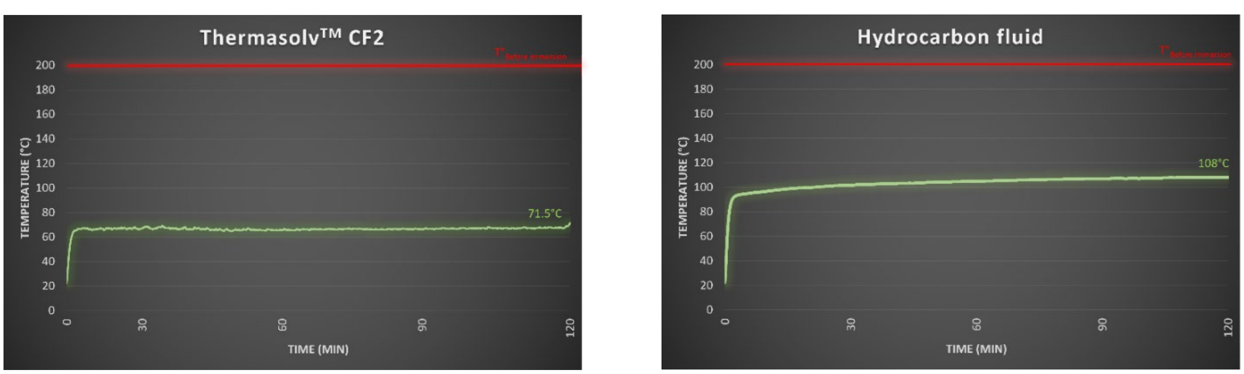
(a) (b) (c)

Figure 4. Flammability test on (a) hydrocarbon oil before bringing a flame (on top) and after (bottom); (b) Thermasolv™ CF2 before bringing a flame (on top) and after (bottom); (c) Thermasolv™ IM6 before bringing a flame (on top) and after (bottom)

As we can see, the hydrocarbon oil doesn't properly catch fire when a flame is brought close to it, but the flame still remains whereas Thermasolv™ fluids neither catch fire nor retain the flame. On top of that, if a flame encounters the vapors of either CF2 or IM6 it is immediately suppressed, which shows that both have extinguishing properties, which is not the case of the oil.

Cooling performances with a heat source:

Before immersing a real server, a simple setup with a ceramic heat source was used. The heat source was immersed in 10L of the cooling fluid being assessed for two hours. Both CF2 and the hydrocarbon oil are single phase immersion cooling fluid, which means that the fluid needs to circulate through a chiller to cool it down before going back to the tank. The temperature of the inlet and outlet were recorded. Fig. 5 shows the results obtained for CF2 and the oil. For CF2 the inlet temperature was 36.2°C and the outlet one was 36°C. For the hydrocarbon the inlet was 34.8°C and the outlet was 34°C.



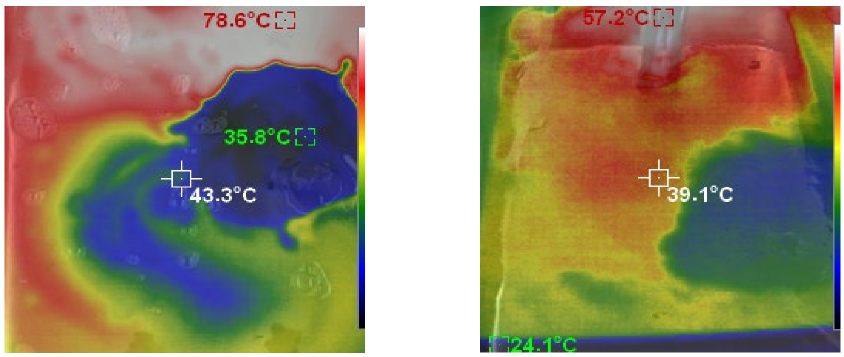
(a) (b)

Figure 5. Cooling performances with a heat source for (a) CF2, (b) hydrocarbon oil

The heat source's temperature before immersion reached 200°C. Once immersed and after two hours, data were collected. We can see that the maximum temperature reached for CF2 is only 71.5°C which indicates a 65% reduction compared to the temperature in open air.

The same has been done with the hydrocarbon oil, however the maximum temperature after a two-hour immersion, is 108°C which is 51% higher than CF2. This shows that CF2 has better cooling performances than the oil.

Additionally, an infrared picture of the bath from the experiment with CF2 and the hydrocarbon were taken and are shown below on Fig. 6.



(a) (b)

Figure 6. Thermal picture of the bath with (a) Hydrocarbon oil (b) CF2

These infrared pictures show us that using CF2 as a cooling fluid gives a better bath homogeneity which could be explained by the way lower viscosity of CF2. Having a better homogeneity will translate into having a better heat dissipation.

Thermasolv™ IM6 was also assessed the same way as both previous fluids. However, since IM6 has a low boiling point (47°C) it will be a two-phase immersion cooling. This means that no pump is needed and instead a coil is put on top of the tank to condense the vapors into liquid.

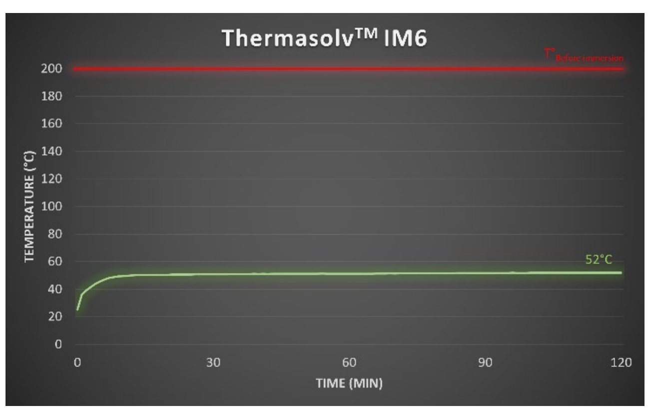


Figure 7. IM6 cooling performances with a heat source

Fig. 7 shows the cooling performances of IM6 with the same heat source used previously. The maximum temperature reached after two hours is only 52°C (compared to 71.5°C for CF2 and 108°C for the hydrocarbon oil). That means that the temperature while immersed is 28% lower than what we can get with CF2 and 52% lower compared to hydrocarbon oil.

Cooling performances with a real server

After assessing the cooling performances using a simple heat source, the next step was to fully immerse a real server into each fluid to determine which would perform the best. This time the volume needed to fully immerse the server was 15L. Before immersing the server, we tried to see how inefficient air cooling was when the CPU is put at 100% load constantly for two hours. Fig. 8 shows the CPU temperature on all four of its cores. Fig. 9, 10 and 11 are the results of the immersion experiment respectively for the hydrocarbon oil, CF2 and IM6. The experiment lasted two hours and the temperatures were recorded every ten minutes.

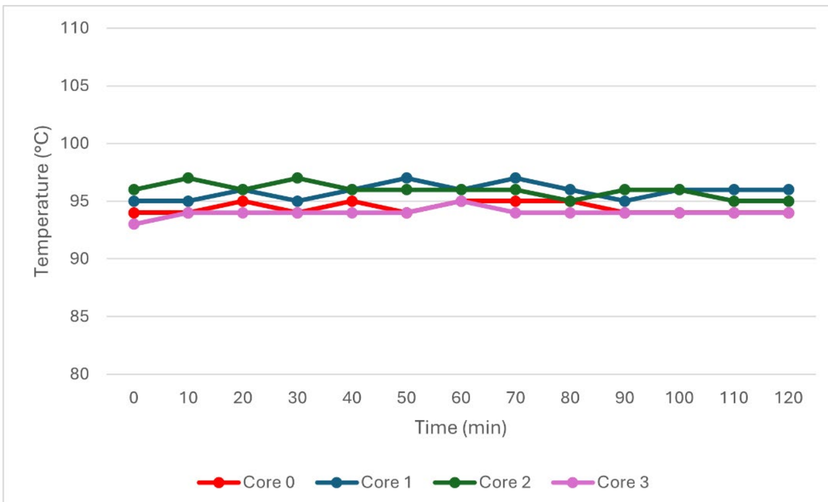


Figure 8. CPU'S core temperature over time with air cooling

The maximum temperature for all four cores recorded by CoreTemp is 97°C for both core 1 and 2 while the temperature for core 0 and 3 reached 95°C. However, it is to be noted that the CPU was no longer working at full capacity after going above a certain temperature because of a safety mechanism. It is very likely that the temperature would have risen more without this.

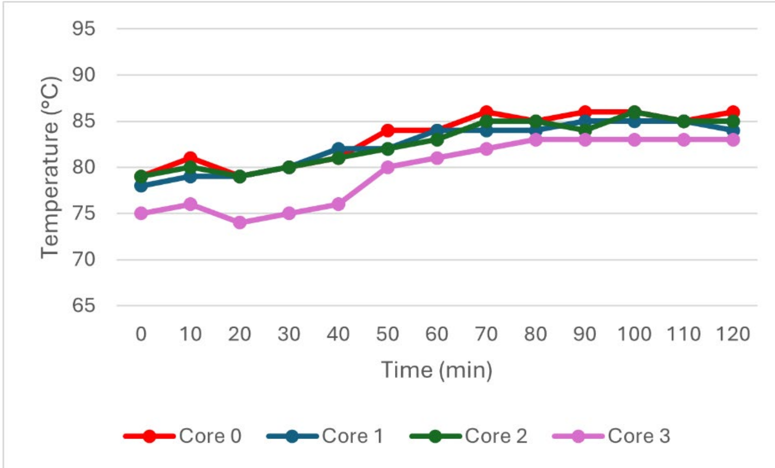


Figure 9. CPU'S core temperature over time with hydrocarbon oil

On Fig. 9 we can see the temperature reached by the CPU on all of its cores when using the hydrocarbon oil as a cooling fluid. After two hours immersion the maximum temperature recorded was 86°C on core 0 and 2. Core 1 had a maximum temperature of 85°C and core 3 reached 83°C.

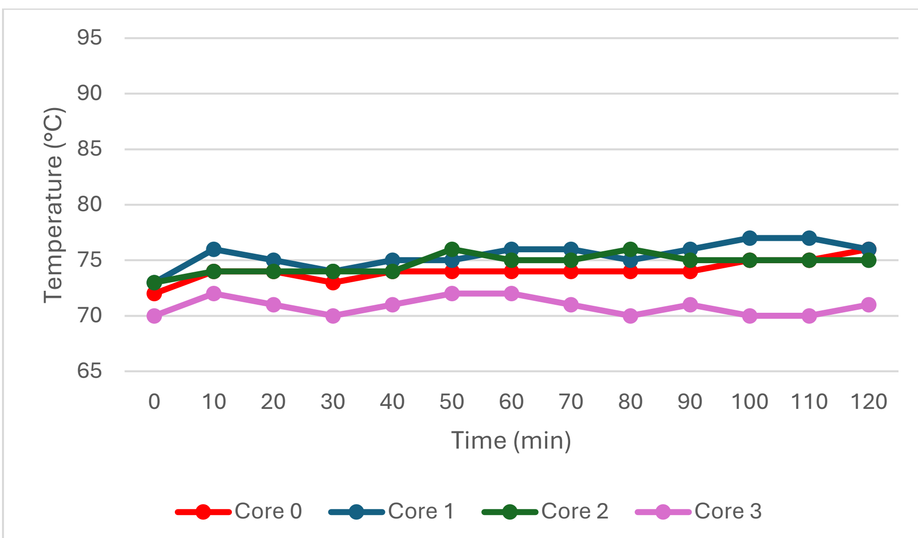


Figure 10. CPU'S core temperature over time with CF2

As shown on Fig. 10, with CF2 the maximum temperature reached by the CPU is 77°C on core 1. Core 0's max temperature was 76, core 2's was 76°C and core 3's was 72°C.

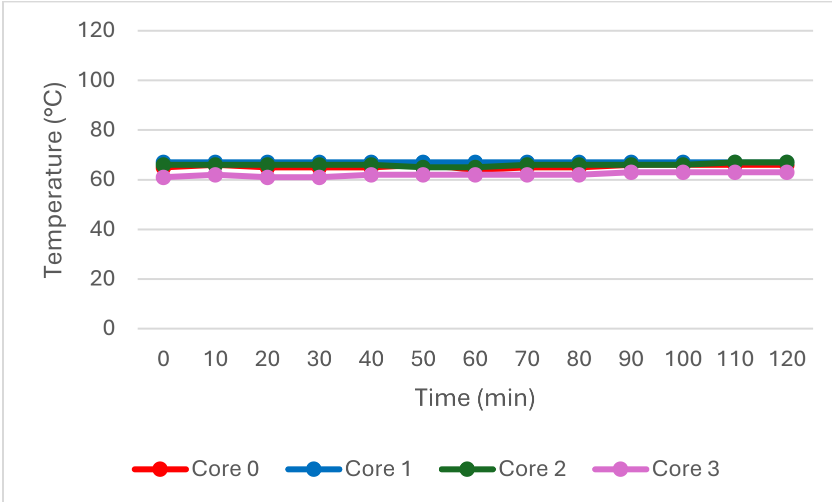


Figure 11. CPU'S core temperature over time with IM6

For IM6 the maximum temperature recorded was 67°C on both core 1 and 2. Core 0's maximum temperature was 66°C and core 3's was 62°C.

Discussions:

Compatibility

The compatibility results in Table 2. show that both Thermasolv™ fluids have a great compatibility with most of the elastomers tested while the hydrocarbon oil showed limited results. This could be problematic in data centers because it means some materials would need to be replaced if such a cooling fluid were to be used. Moreover, these incompatibilities not only are an issue regarding the server components as it damages them, meaning they can become less reliable over time and have their lifetime reduced, but also regarding the fluid properties as it could affect both the heat dissipation ability and the dielectric properties. Either way it is an issue for applications as sensitive as data centers.

Safety

As shown in Table 3. it can be noticed that both Thermasolv™ fluids don't have any flash point whereas the hydrocarbon oil has a flash point of 200°C which could be dangerous in case of a fire occurring nearby. This temperature wouldn't be reached by the server itself, however, if a fire starts the temperature will definitely go over 200°C. For data center application a fire hazard with flammable fluid would be the worst thing to happen as it could lead to losing the servers and thus the data. Additionally, while the oil is not flammable, it can sustain flames if it comes into contact with them. On the other hand, CF2 and IM6 not only aren't flammable but also have extinguishing properties which could be extremely helpful to keep the data safe. Flammability is a major concern, so a non-flammable fluid with fire-extinguishing properties is especially valuable in settings like date centers, where enhanced safety is critical.

Performances

According to the data in Table 1., the hydrocarbon specific heat is 2274 J/kg.K which is way better than CF2 (1087 J/kg.K) and IM6 (1044 J/kg.K). However, the specific heat is a value expressed for one kg of fluid which isn't the best way to compare these fluids since their density is quite different from one another. In order to compare their theoretical ability to dissipate the heat it is better to convert this value to volume instead of mass since the volume used in the experiment is constant. The specific heat per volume now becomes:

Hydrocarbon: 1832.8 J/L.K

CF2: 1972.9 J/L.K

IM6: 1670,4 J/L.K

This changes everything, now in theory CF2 should have a better heat dissipation than the hydrocarbon oil and IM6. Experimentally, the first test with a heat source showed that the hydrocarbon oil was the fluid that dissipated the heat the less whereas IM6 was the most efficient with a temperature recorded of only 52°C after submerging the heat source for two hours. In theory the specific heat per volume for IM6 is the lowest out of the three fluids, however, since it is not single-phase immersion cooling anymore, the latent heat of vaporization has to be considered which reflects how much heat a fluid can absorb as it transitions from liquid to vapor. For IM6 it is 148.8 kJ/L which is 75 times more than the specific heat of CF2 and 81 times more than the specific heat of the hydrocarbon oil. The heat of vaporization compensates the lower specific heat since it requires a huge amount of energy to turn from liquid to vapor state. If we look at the results of the second experiment with a real server, the tendency is kept. With a CPU running at full load the maximum temperature recorded with the oil was 85°C on average while it was only 75°C on average with CF2 and for IM6 the CPU's max temperature was 65°C on average which is extremely efficient if we compare to the maximum temperature recorded with air cooling which was 96°C on average. Having a higher viscosity and a lower specific heat per volume compared to CF2 is what makes the hydrocarbon oil less effective despite having a better thermal conductivity (0.142 versus 0.112 W/m.K for CF2). Thanks to these great performances achieved through immersion cooling we could build more powerful and more dense data centers and keep up with the newest technologies.

Conclusion:

This paper first demonstrated how insufficient air-cooling is when it comes to cooling servers since the CPU reached the maximum temperature allowed when it was put at full load. Air-cooling is still the most prominent technique nowadays, but it can't keep up with the overgrowing demand in power and data center density. It is therefore a necessity to go towards new technology in the future such as immersion cooling. From the experiment results it can be said that immersion cooling, be it single-phase or two-phase, using hydrocarbon oil or fluorinated fluids, offers way better heat dissipation than air cooling. Between all three fluids, the hydrocarbon oil showed the less efficient performances both with a simple heat source and a real server. On the other hand, Thermasolv™ fluids have an excellent environmental and safety profile and at the same time very efficient cooling performances with IM6 being the most efficient, making two-phase immersion the best choice regarding heat dissipation.

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