Setting up an experimental framework for analysing an immersion cooling system

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***Abstract*—This paper compares the cooling-efficiency between air and immersion cooling methods through the implementation of an experimental framework. Short and long term stresses with and without overclocking were run and monitored on 8 identical HPC servers. A statistical analysis using the Mann-Whitney method was conducted to determine whether or not, the temperature differences observed between the servers cooled by immersion and the ones cooled by air were significant.**

The results were promising with immersion cooling achieving better overall cooling performance with low energy consumption as no cooling units were used for the immersion cooling system. A discussion on practical issues encountered using the immersion technology is also included.

***Index Terms*—Data center, Immersion Cooling System, Overclocking, Experimental Evaluation.**

I. INTRODUCTION

To enhance the knowledge regarding immersion cooling performance, this paper directly compares thermal and electrical behaviour of identical high-performance servers cooled either by air or by immersion (single phase) within an Immersion4 prototype[1].

We set up an experimental framework divided into 4 parts: (1) a hardware part including the HPC servers, the Immersion4 tank and the air-cooled datacenter, (2) then a sensor part (internal and external to the servers), (3) a collection and automatic storage part of the experimental data and finally a (4) last part gathering the benchmarks and stresses applied to the studied servers.

The remaining of this article presents the previous and related works (Section II). The experimental framework is then detailed (Section III) followed by the main experimental results and analysis (Sections IV and V). The Section VI focus on the variation of oil temperature and its effect on the servers cooling. Finally, the Section VII details the operational problems we encountered when using the Immersion4 tank.

II. RELATED WORK

In the context of reducing energy consumption and ultimately carbon footprint, the digital sector is a growing concern. In 2019, the Internet represented 10% of the world's electricity consumption and was responsible for 4% of greenhouse gas emissions in the world. Above all, greenhouse gas emissions are increasing (+8% every year) according to [15]. Datacenters account for 19% of the electricity consumed. In the United States, the energy consumed by datacenters was multiplied by 5 in 20 years (from 28 TWh in 2000 to 140 TWh in 2020) [4].

Digital technology, and more specifically datacenters, are becoming an increasingly important energy and environmental issue. For a traditional air-cooled datacenter, 38 to 50% of the total electrical energy consumed is used for cooling [7] [10].

A lot of progress has been made making datacenter cooling systems more efficient, with free cooling, adiabatic cooling, or exothermic buildings for instance. [14] Adiabatic cooling uses the water droplets' latent heat of vaporization to cool hot air. The latent heat of vaporization enables a massive heat extraction compared to a sensible heat exchange (provoked by a temperature difference without any state change). However, adiabatic cooling consumes more water compared to classic air cooled system [16].

In the future, using air as the heat transfer fluid will appear increasingly limited because of the increase in IT equipment power flux. Thus, liquid (using water) or two phase cooling systems (using a refrigerant) have been implemented to dissipate the heat flux more efficiently [14]. Nonetheless, the direct liquid cooling method implies a high pump consumption and non homogeneous temperature.

Immersion cooling has been an interesting alternative for about ten years and has great potential in terms of energy savings.

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[1] https://www.immersion4.com/

Indeed, mineral oil is twice more efficient in terms of heat capacity compared to air. Classic mineral oil has a 2000 $J/kg.K$ heat capacity compared to a 1006 $J/kg.K$ heat capacity for air. A higher thermal density combined with a higher heat exchange coefficient makes immersion technology attractive and able to dissipate a higher thermal flux. For example, [7] estimate the heat exchange coefficient between 30 and 3000 W/m^2K in forced convection for a mineral oil compared to the air (12-200 W/m^2K in forced convection). For a small heating element with a maximum generating heat of 30W, an exchange coefficient of 800 W/m^2K was obtained with a two-phase immersion system [13].

By optimizing some components like the boiler's design, better cooling performance can be achieved with a two-phase immersion system. In [11], the authors experimentally obtained a minimum thermal resistance of 0.035 °C/W for an HPC chips Thermal Desing Power (*TDP*) of 900 W. Their cooling system can theoretically be suitable for HPC chips with a maximal TDP of 1267 W (considering a maximum junction temperature of 105 °C).

Concerning single-phase immersion cooling, experimental benchmarks [7] and simulation models [12] have already been tested. However, those examples do not compare directly two cooling methods on identical and independent HPC servers.

In [9], the results regarding the cooling efficiency and PUE (Power Usage Effectiveness) are encouraging for immersion cooling compared to air cooling. However, this study was carried out for low power servers (inferior to 300 W). For higher power machines, performance and power comparison were performed in [6]. Nonetheless, the immersion system's operational conditions were not studied and the supercomputers compared were not strictly identical.

III. EXPERIMENTAL FRAMEWORK

The paper's main contribution is to compare two different cooling methods. For this purpose, we have set up an experimental framework.

This experimental framework allows us to stress the HPC servers while automatically retrieving and storing our experimental data.

A. Servers configuration

For the studies, we used HP Apollo 2000 (2 Intel CPU 5218, 16 cores/CPU, 12x16 Go of memory) servers, with the same BIOS configuration. The only difference being the absence of fans for submerged servers

Among the Apollo servers, 4 were aircooled and 4 were immersion cooled using an Immersion4 tank.

The air-cooled room was designed to cool hundred of others servers. The HP Apollo were the only ones studied and compared to the immersed servers. In the Immersion4 tank, two other servers were immersed but not used in the studies presented in this article.

B. Cooling methods

Cold air is blown directly onto the servers. The heated air is then extracted from the datacenter room and goes through a heat exchanger and is cooled by cold water. At the exit of the heat exchanger, the cooled air is blown back onto the servers whereas the heated cooling water goes through cooling units before being used again in the heat exchanger. However, in winter, or more generally when the outside temperature is at least below the hot air outlet temperature, outside air is used to pre-cool the data center hot outlet air. This free-cooling results in a reduction in the use of the cooling unit. Free cooling combined with a good room architecture with cold and warm aisles makes it possible to obtain an average Power Usage Effectiveness (PUE) of 1.23. Within this datacenter, one base-plate was dedicated to the HP Apollo servers studied.

The Immersion4 tank is divided into 3 main parts: 2 compartments in which servers are immersed and 1 cooling compartment which contains the oil pan and the heat exchanger (Fig. 1).

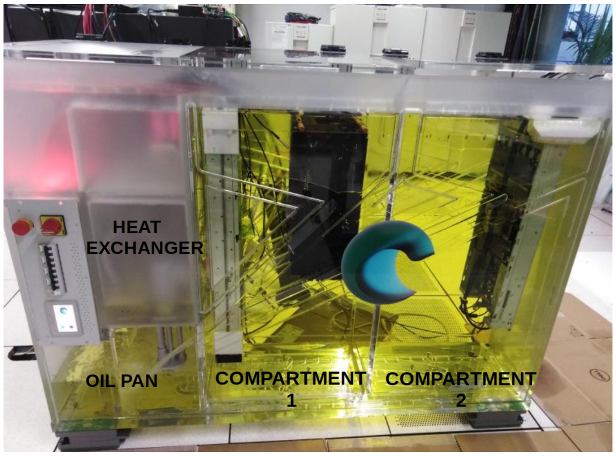

Fig. 1. Immersion4 tank.

The servers are placed in one of the two compartments which can contain up to 250 L of oil. The oil is injected into the lower part of the compartments, heats up when it encounters the servers, and then falls back into the collection tray by overflow. Then, the heated oil goes through the heat exchanger and is cooled by cold water. The cooled oil is pumped back into the compartments from the bottom in a closed loop process. Unlike the air cooling system, the cooling water is not linked to a cooling unit. The water at the exit of the heat exchanger is only cooled by the temperature difference between the water and the environment. We kept the cooling situation unfavorable except for the Section VI-A when we needed to control the oil outlet temperature.

C. *Sensors*

For the servers cooled by air, no additional sensors were installed. We only used the the internal servers' sensors.

Whereas, for the immersion cooling technology, we measured the ambient air temperature with a DHT11 [3] and DHT22 sensors [1]. The oil temperature was monitored using 8 DS18B20 sensors immersed [2] in the compartment which contained our HP servers. Finally, the inlet and outlet cooling water temperature was also monitored by 2 DS18B20 sensors. All the sensors were connected to 4 Raspberry Pis.

For both air and cooling methods, the IPMI protocol and Linux commands were used to measure internal metrics (TABLE I).

Metrics	Unit	Frequency	Source
CPU0	°C	1s	Sensors
CPU1	°C	1s	
mean,CPU0	°C	1s	
mean,CPU1	°C	1s	
power	W	1s	
memory,byte	Ko	1s	
load	unit	1s	Uptime
Cores frequency	MHz	1s	cat /.../scalingcurfreq
RAM1	°C	1s	IPMI
RAM2	°C	1s	IPMI
RAM3	°C	1s	IPMI
RAM4	°C	1s	IPMI

TABLE I
LIST OF ALL THE METRICS COLLECTED.

The metrics *CPU0* and *CPU1* refer to the maximum temperature among the CPUs' cores. The mean of the cores temperature per CPU is also collected and named *mean CPU0* and *mean CPU1*. Finally, *power* measures the power received by each server, *memory byte* gives an indication on the free memory, *load* indicates the total CPU load.

D. *Metrics collection*

For the air and oil test benches, all the metrics measured by our sensors were collected and stored in a database every second using Kwollect [5].

For the air benchmark, we wrote bash scripts allowing Kwollect to retrieve and store all the values generated by the internal servers sensors. For the oil one, we wrote bash scripts (for the internal servers sensors) and python scripts (for the sensors connected to the Raspberry) to collect and store all the metrics wanted. In our case, we considered that the impacts of measuring internal metrics were identical from one server to another and negligible as the generation and collection of these metrics produced a very low load and was therefore negligible.

E. *Experimental methodology*

As previously stated, the main goal was to study the electric and thermal behavior of identical servers exposed to different cooling methods. The servers needed to be stressed the same way. In our case, servers were tested with 2 NAS benchmarks (EP.F and LU.E), 1 stress-ng and 1 stressapptest command.

Between each test, we waited 5 hours for the NAS benchmarks and 4 hours for the stress-ng and stressapp tests to stabilize the oil temperature. All stresses were launched at the same time (Time=0) and 10 times for every server. Thanks to Kwollect, all the experimental data (following the metrics given in TABLE I) were stored automatically in our database. In total, we collected and analyzed 255 hours of experimental data.

IV. EXPERIMENTAL RESULTS

A. *NAS benchmarks*

The NAS benchmarks[2] test high performance servers. The EP test is CPU intensive whereas the LU test is both CPU and memory intensive. Different classes were available for each of these tests which refer to the size of the problem (A for the smallest and F for the biggest problem size). The F class was chosen for the EP and the E class for the LU to obtain an execution time around 2 hours for each benchmark. We ran the EP and LU benchmark 10 times each.

1) NAS benchmarks for $f = 2,3GHZ$*:* The NAS benchmarks were first executed for a fixed CPU frequency of 2.3 GHz.

On the figures Fig. 2 and Fig. 3 we can see that no server exceeded its temperature limit which is around 90°C for all the experiments. The immersion technology cools the servers down to a temperature that allows the servers to function.

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[2] https://www.nas.nasa.gov/software/npb.html

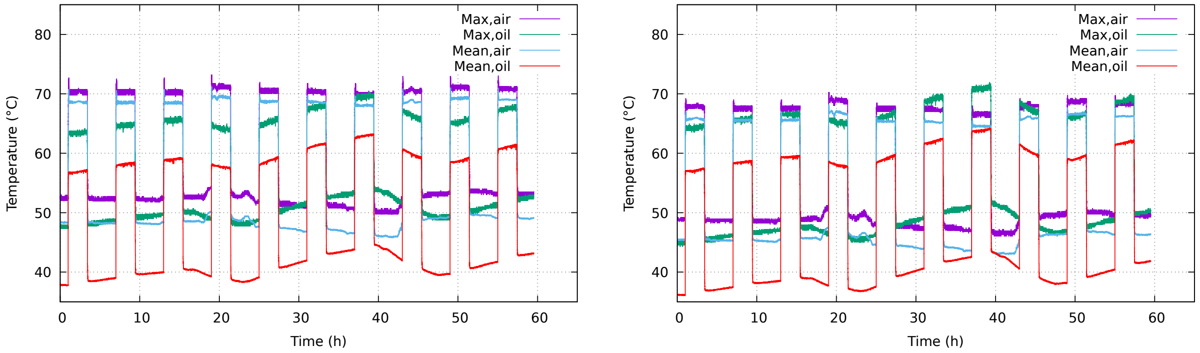

Fig. 2. Average temperature of the mean and maximal cores temperatures for the CPU0 (left) and CPU1 (right) during the EP tests.

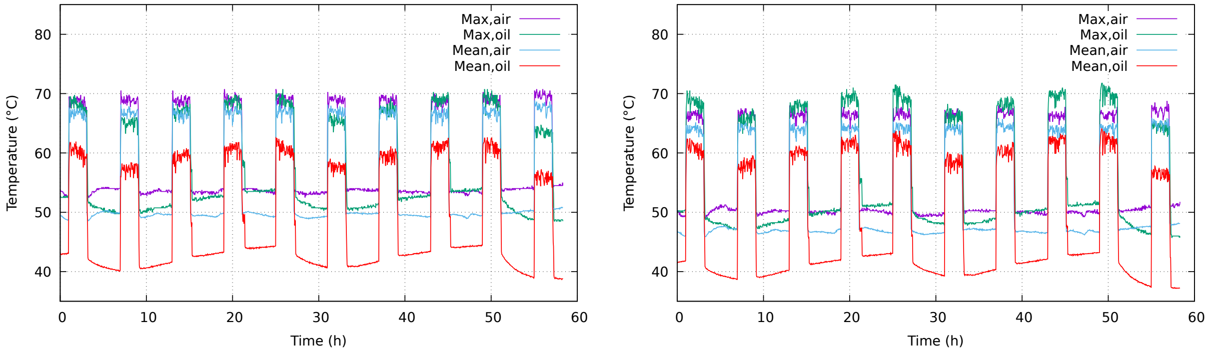

Fig. 3. Average temperature of the mean and maximal cores temperatures for the CPU0 (left) and CPU1 (right) during the LU tests.

However, contrary to the air cooling system, the initial oil temperature varies from an experiment to another. It varies from 22.9°C to 32.4°C. Therefore, servers' temperatures cooled by oil vary more from one experiment to another compared to the servers cooled by air. To take these variations into account, the average CPU temperatures for the 10 experiments were compared.

Despite unfavorable cooling conditions, with an ambient temperature equaled to 29°C and a cooling water temperature above 23°C for all the experiments, the mean cores temperatures, on average, are lower for the immersed servers compared to the servers cooled by air (TABLE II).

The temperature gap is more important for the CPU0 compared to the CPU1. Indeed, in the air cooling configuration, the cold air cools and goes through the CPU1 before cooling the CPU0 which means that the air used to cool the CPU0 is hotter. For the CPU0, on average, the temperature gap can reach 9.1°C for the EP test which represents a relative margin of 13.4% compared to the immersed servers' CPUs' temperature.

	EP,CPU0	EP,CPU1	LU,CPU0	LU,CPU1
$\Delta T_{mean}^{oil-air}$	-9.1	-5.6	-7.0	-3.7
$\Delta T_{max}^{oil-air}$	-4.3	-0.5	-1.3	1.7
$\Delta T_{oil}^{max-mean}$	6.6	7.2	7.9	7.8
$\Delta T_{air}^{max-mean}$	1.9	2.1	2.2	2.4

TABLE II
Average CPU temperature gap in °C between the servers cooled by air and by oil during the stress periods.

The temperature differences are less important for the maximal cores temperature with a maximal relative margin of -6.5% for the CPU0 during the EP tests. On average, the CPU1's maximal cores temperature is even higher for the servers immersed during the LU test (+ 2.6 %).

Immersion cooling seems to cool the CPUs' cores in a less uniform way. We can verify this by comparing the differences between the mean and the maximum cores temperatures within each CPU for each NAS benchmark (TABLE II). In average, this gap is more than 3 times superiors in the oil compared to the air. This difference was found in the 10 experiments, for each benchmark.

The oil's viscosity coupled with the servers' face-to-face positioning may explain this less homogeneous cooling phenomenon within the CPUs in the oil.

The temperature of the RAM strips for the servers cooled by immersion appear to be significantly lower compared to the ones cooled by air, down to 32.0% lower for the RAM2 (TABLE III).

	RAM1	RAM2	RAM3	RAM4
T^{air} (°C)	44.2	46.4	38.8	40.9
T^{oil} (°C)	31.8	31.6	31.1	31.2

TABLE III
AVERAGE TEMPERATURE FOR EACH RAM OF EACH SERVER DURING THE 10 LU RUNS.

2) NAS benchmarks with overclocking: The EP benchmarks were run 10 times but, this time, with different settings for the CPUs' frequencies. All the servers had their frequency set to 1.0 GHz during the IDLE mode. During stress mode, the servers cooled increased their CPU frequency to 2.3 GHz whereas the servers cooled by immersion kept a constant frequency of 2.8 GHz during the stress duration.

The overclocking increased the power consumed by immersion-cooled servers. On average, 1212 W for the 4 servers immersed and 1067 W for the 4 servers cooled by air (+13.5%). Overclocking also means better performance with lower run time, 146 minutes for the servers cooled by immersion and 177 minutes for the servers cooled by air (-17.4%). The servers overclocked dissipated more heat. However, immersion cooling still managed to cool down efficiently the immersed servers with lower temperatures compared to the servers cooled by air without overclocking (down to -6.2 % for the CPU0). Maximum core temperatures are however higher for immersion-cooled servers than for air-cooled servers for both processors (TABLE IV).

	EP,CPU0	EP,CPU1
$\Delta T^{oil-air}_{mean}$	-3.8	-0.5
$\Delta T^{oil-air}_{max}$	0.8	4.7
$\Delta T^{max-mean}_{oil}$	6.6	7.2
$\Delta T^{max-mean}_{air}$	1.9	2.0

TABLE IV
AVERAGE CPU TEMPERATURE GAP IN °C BETWEEN THE SERVERS COOLED BY AIR AND BY OIL DURING THE OVERCLOCKING TESTS.

B. Long term stress

With the NAS benchmarks, the duration time for each test could not be controlled. That's why we used `stress-ng` and `stressapptest` to apply a specific stress duration to servers and test the immersion cooling system for longer stress time.

Both CPU and memory intensive stress were launched 10 times for a 3 hours duration each. Then, the process was repeated with a 60 hours duration. The `stress-ng` command generated the CPU intensive stress:

```
stress-ng --matrix 0 -t 3h
stress-ng --matrix 0 -t 60h
```

whereas the `stressapptest` tool generated the memory intensive stress:

```
stressapptest -C 16 -m 16 -i 16 -W --cc test -s 10800
stressapptest -C 16 -m 16 -i 16 -W --cc test -s 216000
```

1) Stress-ng and stressapptest: The results obtained followed the same trend compared to the NAS benchmarks without overclocking(IV-A1). For the stress-ng tests, the mean and maximal cores temperatures were lower for the immersed servers (respectively down to a maximum of -13.5% and -5.7% for the CPU0). The maximal cores temperatures differences are insignificant for the CPU1 (+ 0.1%). The temperatures gap within a CPU is still greater for the servers cooled with oil. The maximum relative gap are 4.1 and 3.7 times higher compared to the ones in the air, respectively for the CPU0 and CPU1 (TABLE V).

	CPU0	CPU1
$\Delta T^{oil-air}_{mean}$	-9.2	-5.2
$\Delta T^{oil-air}_{max}$	-4.0	0.1
$\Delta T^{max-mean}_{oil}$	7.0	7.1
$\Delta T^{max-mean}_{air}$	1.7	1.9

TABLE V
AVERAGE CPU TEMPERATURE DIFFERENCES IN °C BETWEEN THE SERVERS COOLED BY AIR AND BY OIL DURING THE STRESS-NG TESTS.

The RAM strips temperatures are lower in the oil (down to -34.3% for the RAM strip 2) as seen in the TABLE VI.

	RAM1	RAM2	RAM3	RAM4
T^{air} (°C)	40.6	42.3	34.6	36.3
T^{oil} (°C)	27.9	27.8	27.3	27.4

TABLE VI
AVERAGE TEMPERATURE FOR EACH RAM OF EACH SERVER DURING THE 10 STRESSAPPTEST RUNS.

2) 60 hours stress test: In this part, focus will be given to the oil temperature stability (without cooling unit) and its effect on CPU temperatures for a long CPU intensive stress duration.

Once again, the mean cores temperatures were lower for the servers cooled by oil and the gap was smaller for the maximal cores temperatures (Fig. 4).

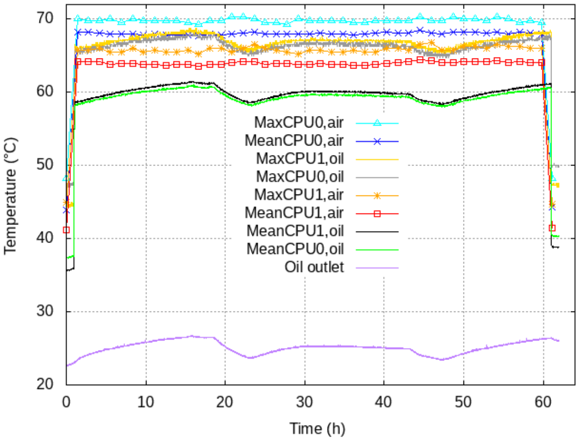

Fig. 4. CPU temperature and oil outlet temperatures during the stress-ng test.

During the 60 hours stress, the oil temperature did not vary uniformly. Instead, there was a sinusoidal like variation with a minimum temperature of 22.3°C and a maximum temperature of 25.6°C. CPU's maximal and mean cores temperatures for the servers cooled by immersion followed the same trend as the oil temperature with a sinusoidal like variation. During the 60 hours CPU intensive stress, CPU temperatures varied more for the servers cooled by oil compared to those cooled by air (TABLE VII).

	ΔT^{CPU0}_{mean}	ΔT^{CPU1}_{mean}	ΔT^{CPU0}_{max}	ΔT^{CPU1}_{max}
Air (%)	4.4	3.8	2.6	2.8
Oil (%)	7.0	6.9	5.8	6.3

TABLE VII
MAXIMUM RELATIVE VARIATION FOR THE MEAN AND MAXIMAL CORES TEMPERATURE DURING THE STRESS-NG TEST.

The maximal mean cores temperature variation of immersed servers is on average 1.7 times more important compared to the same variations of air-cooled servers. Concerning the maximum cores temperatures variation, maximum temperature variation observed are (on average) 2.3 times higher for servers in oil compared to the servers in air.

The air inlet temperature was kept constant at 21°C which means that CPU temperature remains stable if the cooling and stresses conditions are constants.

The oil's temperature variation is not induced by a CPU's temperature variation (TABLE VII), it was mainly influenced by the cooling water temperature, which fluctuated between day and night, rather than the immersed servers' thermal load.

V. STATISTIC ANALYSIS

A. The Mann-Whitney method

In Sections IV-A and IV-B lower average cores and RAM strips temperatures were obtained for immersion-cooled servers. However, some factors can affect the experimental results. For example, instrumentation can impact our experimental results but we considered it to be negligible in our case as explained in the Section III-D. However, the servers' production themselves can lead to differences in thermal behaviour of seemingly identical servers. The variability of measurements from one experiment to another, as seen in the Section IV-A1 can also distort interpretations of results. Therefore we decided to carry out a statistical analysis. The aim of this statistical analysis was to determine whether or not, the temperature differences observed per group of servers were significant and due to the cooling method rather than any other external factors.

The Mann-Whitney model assesses how close the data's distribution from a group, coming from the same population, are. In this study, the population corresponds to all HP Apollo servers, the first group to the 4 air-cooled Apollo servers and the second group to the 4 immersed servers. For each run of each benchmark and stress, each member of each group is assigned the average temperature for the whole run (only the stress part). For example, to test the significance of the differences observed in the CPU0's maximum cores temperatures, we assigned to one server cooled by air, the CPU0's average maximum cores temperature value during the whole EP run of experiment 1 and so on for each server, each run and each metric analysed (RAM strips temperatures, mean and maximal cores temperature).

To determine the significance of the observed temperature differences using the Mann-Whitney test, the null hypothesis H0 in our case corresponds to the postulate: "RAM1's temperature in the air is not significantly higher than RAM1's temperature in oil". The alternative hypothesis H1 is "RAM1's temperature in air is significantly higher than RAM1's temperature in oil". The level of significance (probability of rejecting H0 when H0 is true) α is set at 5%. Based on RAM1s' average temperature values in each server of each group, we calculate the p-value, the smallest level of significance that would lead to rejection of the null hypothesis. If the p-value is lower than the chosen level of significance

(α), the H0 hypothesis can be rejected concluding that the observed difference is statistically significant. In our case if the p-value obtained is below 5%, we have a strong suggestion that the temperatures of the oil-cooled servers are significantly lower or higher (depending on the case) than the temperatures of the air-cooled servers.

B. *Results of the Mann-Whitney tests*

Concerning the RAMs' strips temperatures, the Mann-Whitney test (with $\alpha = 5\%$) considered the temperature differences as significant for each RAM strip and each test (TABLE VIII).

Tests	RAM1	RAM2	RAM3	RAM4
$LU2, 3GHz$	1.5%	1.5%	1.5%	1.5%
$LU2, 8GHz$	1.5%	1.5%	1.5%	1.5%
$stressapptest60h$	1.5%	1.5%	1.5%	1.5%
$stressapptest3h$	1.5%	1.5%	1.5%	1.5%

TABLE VIII
P-VALUE FOR THE MANN-WHITNEY TEST CONCERNING THE RAM STRIP TEMPERATURES.

Without overclocking, for each CPU intensive stress and with $\alpha = 5\%$, the Mann-Whitney tests concluded that the temperature differences observed between servers cooled by oil and servers cooled by air are significant for the mean cores temperatures and the gap between CPUs' mean and maximal cores temperatures. However, the maximal cores temperatures differences observed are not significant. With overclocking, the mean cores temperatures are still lower for the immersed servers but not significantly. CPU1's maximal temperature is significantly higher for the immersed servers compared to the servers cooled by air. (TABLE IX).

Statistical analysis shows that immersion cooling cools server cores (without overclocking) and RAM strips better on average than air cooling.

Conductors with high current densities (as it applies to CPUs) are more damaged by the electromigration phenomenon than by the Joule effect. Electromigration's effect is limited by lower temperatures [17]. Thus, immersion cooling may increase the CPUs' lifetime.

Moreover, lower mean cores temperatures achieved by immersion cooling are promising for meeting the challenges of increasing CPU's *TDP*. With a more efficient CPU cooling and therefore a lower temperature rise, servers can increase CPU frequencies and thus gain in performance.

VI. OPERATIONAL CONDITIONS

A. *Pump shutdown*

One of the major problems related to the datacenter is safety. If the cooling system shut down in a classic datacenter cooled by air, fire can occur. The OVH datacenter in Strasbourg in 2021 is a reminder of the danger datacenters can represent. With immersion cooling technology, fires are far less likely to happen thanks to the oil's greater thermal inertia compared to the air which enables a higher response time in the event of a breakdown. Nonetheless, we wanted to simulate a cooling failure by shutting down the tank circulation pumps. Thus, we launched the following command:

```
stress-ng -all -0 -t 120h
```

which applies all the available stressors to all the CPU at the same time for 120 hours (Fig. 5).

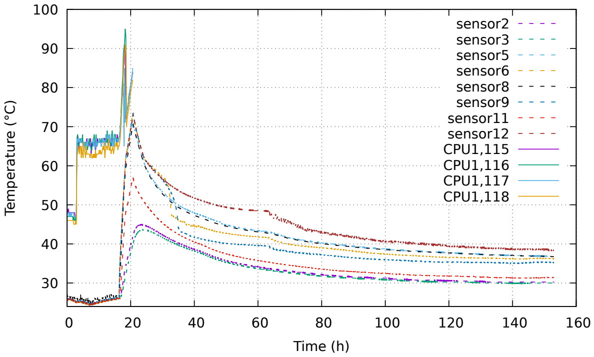

Fig. 5. Evolution of oil and CPU temperature after pump shutdown

After 16 hours, pumps were stopped. Immediately, the temperature of both oil and CPUs starts rising. Around, the 20th hour, servers stopped functioning by reaching their critical temperature (around 90°C). At the same moment, oil's temperature reaches a peak at 71°C (sensor 6). Oil's temperature decreases due to heat loss to the environment.

Firstly, 4 hours and 20 minutes elapsed between the moment when the two circulation pumps stopped and the moment when the servers went into safety mode. Note that this intervention time is valid for a maximal ratio of 2.4 kW/m³ of oil.

This experiment also provides the oil temperature limit that operators should not exceed in order to avoid reaching the CPU temperature limit. According to the Fig. 5, the operational limit temperature for mineral oil, in our conditions, is between 55°C and 60°C. This operational limit temperature also gives information about heat recovery. As water/oil heat exchangers are not infinite, the cooling water's outlet temperature will necessarily

Tests	Mean,CPU0	Mean,CPU1	Maximal,CPU0	Maximal,CPU1	$\Delta T_{max-mean}$
$EP2.3GHz$	1.5	1.5	5.6	5.6	1.5
$EP2.8GHz$	9.7	44.3	44.3	1.5	1.5
$stress - ng3h$	1.5	3.0	23.5	44.3	1.5
$stress - ng60h$	1.5	3.0	23.5	23.5	1.5

TABLE IX
COMPARISON BETWEEN THE P-VALUE AND THE $\alpha = 5\%$ PROBABILITY FOR UNIDIRECTIONAL MANN-WHITNEY TESTS.

be lower than the inlet oil temperature in the heat exchanger. Therefore, the critical oil temperature provides an indication of the expected temperature level for heat recovery. This temperature level will then condition the use of this cooling water. The oil's critical temperature gives a first indication of the ideal operating conditions. The ideal operating conditions combine both a sufficient cooling of the servers and at the same time a low consumption cooling need and a heat recovery at a level of temperature sufficiently high to be valued at best. With a 50°C water outlet temperature, domestic water can be pre-heated or used as a heat source for an absorption machine [8]. Moreover, high oil temperature level means lower cooling requirement and therefore a lower overall energy consumption.

B. Variation of oil outlet temperature

Activation of the cooling unit and cold water's arrival at 13°C allowed us to control the temperature of the oil leaving the servers'compartment. We ran EP.F.x tests for oil temperatures ranging from 25°C to 60°C, increasing the set point by 5°C between each test (Fig. 6).

The immersed servers' mean cores temperature exceeds the air-cooled mean cores temperature from an oil outlet temperature of 55°C (only for the oil's CPU0s). Then, from an oil outlet temperature equaled to 50°C, the immersed servers' CPU0 and CPU1 maximal cores temperatures exceed the air-cooled CPU0 and CPU1 maximal cores temperatures. The oil's maximum operating temperature is around 60°C as seen in Section VI-A with a corresponding maximal cores temperature of 85°C for both CPUs.

We measured the CPU temperatures as well as the air and oil temperatures next to the CPUs. The heat dissipated can be expressed by the simple Equation (1):

$$Q = US\Delta\ T \tag{1}$$

With Q (W) the heat dissipated by one CPU, U $(W/(m^2.K)$ the global heat transfer coefficient, ΔT (K) the temperature difference between the CPU and the oil or air next to the CPU and S (m^2) the CPU's surface. By assuming all the servers dissipated the same amount of heat, the CPUs had the same surface and by knowing ΔT, we can determine the ratio of the exchange coefficients in air and oil (Equation (2)):

$$\frac{U_o}{U_a} = \frac{\Delta\ T_a}{\Delta\ T_o} \tag{2}$$

The cold air temperature known corresponded to the air inlet temperature for the CPU1. The air inlet temperature for the CPU0 was hotter and unknown. Strictly speaking, the closer the cores temperatures in air and oil are, the closer the heat dissipation in air and oil is. This is due to Joule effect dissipation and leakage currents which are proportional to the CPU's temperature. The increase in leakage currents and the Joule effect leads to higher power consumption and therefore higher thermal dissipation. Thus, we calculated the global heat transfer coefficient ratio for the CPU1 and a 60°C oil outlet temperature.

This global heat transfer coefficient is 1.4 higher for the oil compared to the air. The ratio seems low. However, during these tests, the oil flow was really low compared to a high air flow constant and equaled to 1115 L/s. Thus, we did not have the same regime flow with a natural convection regime for the oil compared to a forced convection for the air cooling. But, for the air as the heat transfer fluid, the ratio between a heat transfer coefficient with a forced and with a natural convection can vary from 4 to 12. Therefore, the heat transfer coefficient ratio between oil and air (equaled to 1.4) is positive and highlight the better heat exchange achieved by the oil.

VII. PRACTICAL FEEDBACK

A. Tank and servers conception

The Immersion4 tank used was designed to cool 20 U servers. First, the floor of the room in which this type of tank is meant to be installed must be able to support at least 900 kg/m^2. One of immersion cooling's promises is to limit the space required to cool an equivalent amount of servers compared to conventional air datacenter. Based on this Immersion4 tank, the compactness and lower complexity of the installation are not so obvious.

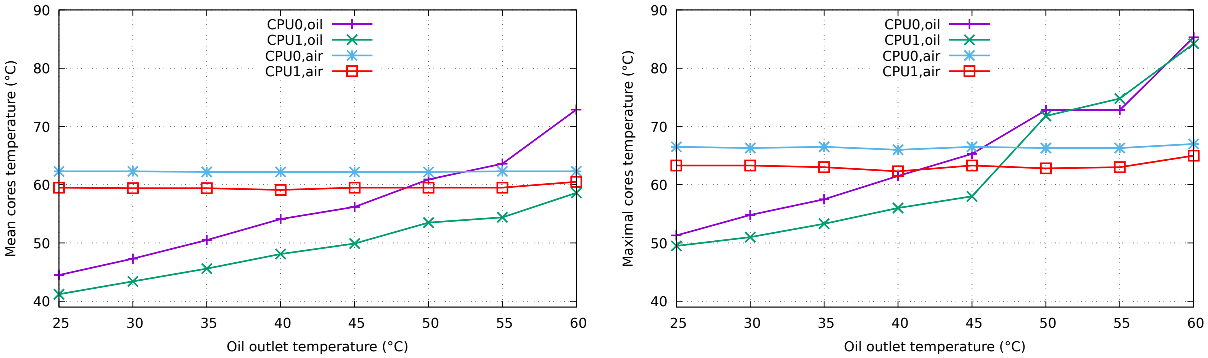

Fig. 6. Mean (left) and maximal (right) cores temperatures for various oil outlet temperature.

First of all, the Immersion4 tank is 1.3m high, which requires a lifting gantry to lift the servers out of the oil for maintenance purposes. However, in the case of aligned tanks, it would be necessary to use a lifting gantry fixed on the ceiling since the cold water inlet is located on one side of the tank. Better compactness and simplicity of use can therefore be achieved by connecting the cold water inlet from under the tank and by limiting the height of the tank.

The height of the tank can also be optimized by developing servers that are specifically designed to be cooled by immersion.

Moreover, all servers had to be adapted before immersion by removing the fans or the thermal paste for example. It is also very important to note that a hard drive disk cannot operate while immersed. However, flash memory (such as SSD) should work, but we have not tested that yet. All labels (and stickers) should also be removed. In our case, one of the labels on the HP servers had not been removed and settled at the bottom of the tank.

Finally, as far as the design of the Immersion4 tank is concerned, with more than 6 servers, we probably would have a space issue to pass our cables in a conventional manner.

B. Oil properties

We used an oil specially designed for Immersion4 tanks: the Ice Coolant. The oil's good thermal proprieties enabled to cool the servers efficiently since September 2021. The oil has never lost its dielectric character and no damage has been observed on the servers immersed, which have perfectly operated in the Ice Coolant. However, Ice Coolant must be handled with personal protective equipment, as skin allergy reactions have been observed after handling this oil.

The oil also damages servers and probes cables, which has the effect of stiffening them, and that in less than a week for the cables of our DS18B20 probes. In 7 months, only 2 DS18B20 sensors have had to be replaced which indicates that the stiffening of the cables does not seem to harm them. However, increased vigilance is required as the stiffening of the cables makes it easier to disconnect the power supply cables. Unintentional disconnection of these cables has already been observed, causing a temporary shutdown of the servers.

The oil also tends to rise up the cables by capillary action. The leaks forced us to add about 20 liters of oil, twice in 7 months, to maintain the circulation and cooling of the oil. To avoid these losses, it would be ideal to place the entire cabling at a height higher than the tank's height.

At last, over time, the oil becomes dirty. In September 2021, the oil was transparent whereas, in May 2022, the oil had a yellowish color. This process does not affect the functioning of the tank, but filtering is recommended. With the Immersion4 tank, it is possible to filter and purify the oil without stopping the tank operation.

VIII. CONCLUSION

This paper aimed to evaluate the cooling effectiveness of immersion cooling compared to conventional air cooling. Identical stresses were applied to 8 identical HP Apollo servers (4 cooled by air and 4 cooled by immersion) to compare the thermal and electrical behavior between servers cooled by immersion and servers cooled by air.

For the NAS benchmarks, the CPUs' mean cores and RAM strips temperatures were significantly lower for the immersed servers (respectively down to -13% and -32%). The CPU's maximal cores temperatures, for their part, were not significantly different according to the Mann-Whitney method (Section IV-A1).

CPUs' temperatures are significantly less homogeneous for immersion-cooled servers than for air-cooled servers. Among each CPU, the temperature differences are, on average, 3.5 times greater for the immersed servers than for servers cooled by air (Section IV-A1).

With a 22% CPU frequency increase for the servers cooled by immersion, the temperatures observed were not significantly different or higher (except for the CPU1's maximal cores temperature) compared to the air cooled servers temperatures (Section IV-A2).

Without the use of a cooling unit, the immersion technology cooled efficiently the servers in comparison with the air cooling technology. Moreover, the oil temperature remains stable under long stress conditions (Section IV-B).

The results are promising for meeting the servers' growing cooling needs while limiting the environmental impact. Indeed, we obtained a global heat transfer 1.4 times superior for the oil compared to the air (Section VI-B).

In near future, we will investigate the reasons for less homogeneous cooling achieved by immersion cooling.

In addition, further experiments need to increase the tank's heat load to enable more relevant calculation of the PUE. A precise energy consumption and recovery estimation will be conducted at different oil operational temperatures to find the best compromise between efficient server cooling and cooling energy consumption. The experimental framework will remain the same as data from new servers can be added easily to the existing database thanks to Kwollect.

Future work will also necessarily include monitoring oil's effects on servers, cables, sensors, and other equipment immersed in it.

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