Proceedings Paper:

Chi, YQ, Summers, J, Hopton, P et al. (4 more authors) (2014) Case study of a data centre using enclosed, immersed, direct liquid-cooled servers. In: Proceedings of the 30th Annual Semiconductor Thermal Measurement and Management Symposium. SEMI-THERM 2014, 09-13 Mar 2014, San Jose, CA. Institute of Electrical and Electronics Engineers (IEEE) , pp. 164-173. ISBN 978-1-4799-4374-6

https://doi.org/10.1109/SEMI-THERM.2014.6892234

Case study of a data centre using enclosed, immersed, direct liquid-cooled servers.

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Abstract

The growth in demand for Information Technology (IT) systems and the requirements to better control carbon emissions is a large challenge for data centre design. Air-cooled data centres are becoming more efficient by layout and the adoption of compressor free cooling, but for higher densities, further efficiencies can be achieved with liquid (water) cooled systems, where liquid is either brought to the cabinet or is fed directly into the IT systems. This paper makes a comparison of the full energy consumption between hybrid air-cooled and direct liquid-cooled systems based on real operational systems using comparable IT components. The results based on real data demonstrate a significant level of energy reduction for a high density data centre solution that uses enclosed, immersed, direct liquid-cooled servers.

Keywords

Direct dielectric liquid cooling, immersed microelectronics, data centre cooling.

1. Introduction

In the case of higher power consumption and denser Information Technology (IT) equipment being deployed, the temperature on the microelectronic components becomes critical and traditional air-cooled methods are being pushed to their thermal limits [1]. One of the most common solutions in use today is chiller and air conditioning to gain a lower temperature gage in order to maintain the microprocessor temperatures within the IT equipment limits [2]. Thus an air-cooled based data centre can achieve a higher IT density and performance, but the use of fans and chillers are extra energy costs that result in lower energy efficiency.

Alternatively, more advanced cooling technologies are being developed to improve the cooling efficiency, where chilled water enters the data centre. This work considers two recent advanced cooling methods that use chilled water to the datacom cabinet and are compared for their energy efficiency.

1.1 Advanced cooling technologies

An approach that can improve energy efficiency, but maintain the performance of the data centre is to include liquid / water to the cabinets in the data centre cooling design [3]. This approach offers an improvement over traditional air-cooled system by moving the water loop closer to the running integrated circuit (IC) components; solutions such as back-door water-cooled heat exchangers [4] and water-cooled blocks [5] are becoming more popular in a bid to achieve greater energy efficiency within the data centre. Moving the water loop to the cabinet reduces the travelling distance of conditioned air, nevertheless such types of hybrid liquid-water cooled solutions are still based on air-cooled design as depicted by the coloured arrows in Figure 1.

To achieve an energy-efficient cooling performance, the next generation, high-density, data centre design needs to be based on a solution that eliminates the requirement for air heat transfer and be replaced by direct liquid-cooling. There are a number of direct liquid-cooled data centre concepts and designs which rely on the use of non-conducting (dielectric) liquids that are either pumped [6], rely on phase change [7] or make use of natural liquid convection [8] which claim to have higher efficiencies than conventional designs.

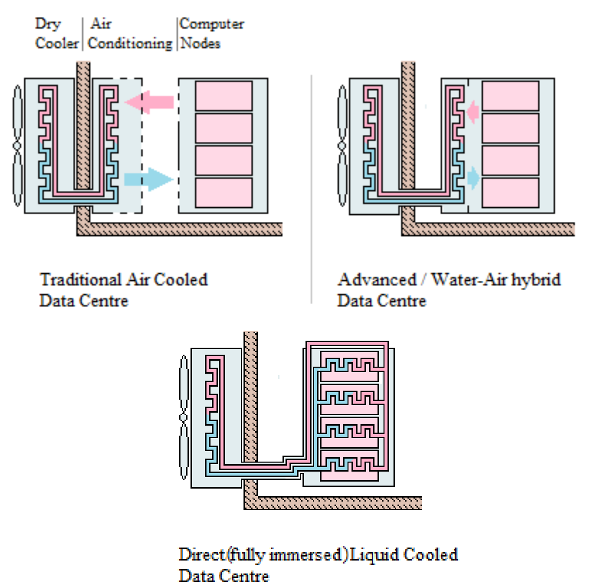

Figure 1 Layout diagrams of different types of data centre solution

1.2 Energy efficiency of data centres

To evaluate the efficiency, or rather the effectiveness of the consumed power, of a data centre, one of the most common metrics in use is the Power Usage Effectiveness (PUE) [9]. The PUE is stated as the total facility power usage divided by the IT power usage;

$$\text{PUE} = \frac{\text{Total Facility Power}}{\text{IT Equipment Power}}$$

The total facility power includes all of the IT equipment power, the supporting power for lighting and monitoring, power distribution and cooling within the data centre building. The IT equipment load generally means everything inside the server / computer, storage and network cabinets.

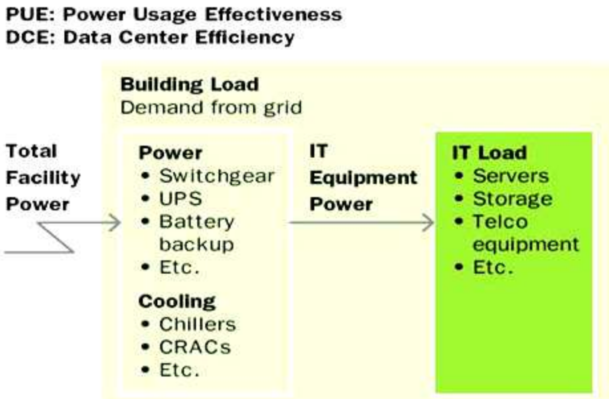

Figure 2 Illustration of how PUE value is calculated in a data center [9].

Most data centre IT infrastructure has some fan based cooling components, such as on central processing units (CPUs) and within rack mounted power supply units (PSUs). In this case their energy consumption is included in the IT Equipment Power (the denominator of the PUE calculation). Therefore, the calculated PUE value of the data centre would become smaller (which may appear desirable) with larger inefficiencies of the IT fan based cooling components, but the true overall energy efficiency of the data centre would be worse when compared to systems that have fewer or no cabinet level fans. Brady et al [9a] discussed such issues with the PUE calculation.

The Performance per Watt (PPW) is easy to understand, since it is the performance under unit power load and usually measured as FLOPS/W, where the term FLOPS refers to the number of Floating-point Operations per Second, but its value of IT work is still software application dependent [11]. In High Performance Computing (HPC) the TOP500 [12] listing is used as a measure of system performance since it is based on maximal linpack performance whatever the energy cost, whereas the GREEN500 [13] listing uses PPW. For example, the BlueGene/Q system built by IBM had the highest PPW back in November 2010 running at 1.684 GFLOPS/W [43]. However, the PPW value is somehow too specific to describe the performance of a general data centre since;

1. FLOPS is one of many performance metrics to measure system performance and is really specific to compute intensive operations such as HPC;
2. Different computer hardware or even different software has an influence on the results of FLOPS performance, for example between CPU and GPU computing [15]; and
3. The FLOPS/W description might only be a useful comparison metric in which 2 data centers have similar hardware structures or identical software application requirements.

The PUE and PPW metrics are complementary in expressing the energy efficiency and task performance of a data centre and therefore both units will be used in this work to evaluate the performance of a data centre.

2. Fully immersed liquid-cooled data centre system

The fully immersed direct liquid-cooled data centre solution, which is used to provide data for the energy calculations used later, was built and supplied by Iceotope Ltd. [15] and uses the natural convective properties of the fluoro-organic dielectric coolant. The heat transfer from the microelectronics to the water jacket relies on density driven natural convection. Figure 3 shows how the dielectric liquid is in direct contact with the microelectronic components and low profile heat sinks.

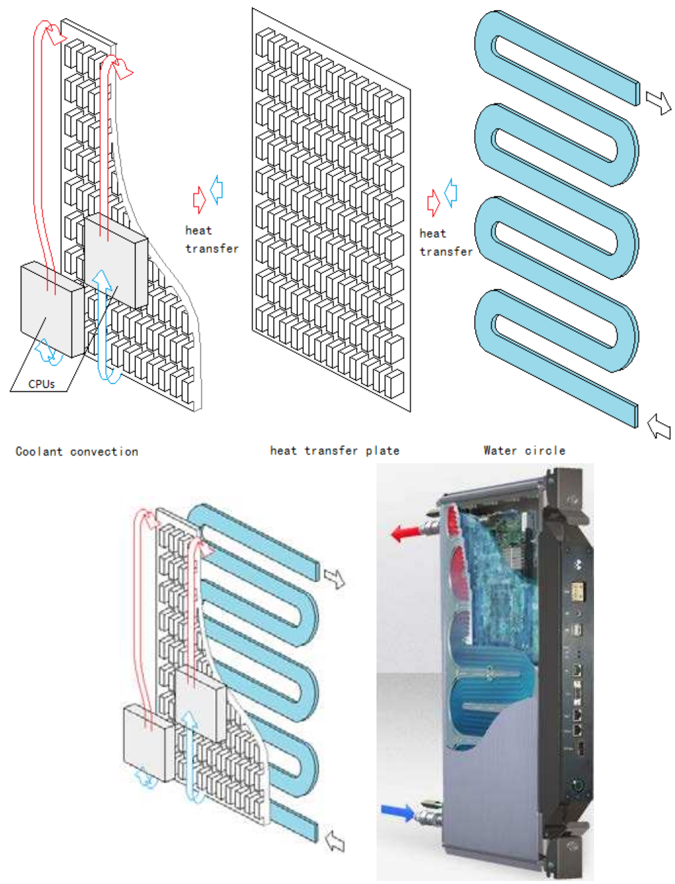

Figure 3 Liquid-immersed system module in detail

The module shown in Figure 3 has quick connect valves that enable it to be hot-swappable in a cabinet that has a carefully designed water circulation system that is thermally coupled to transfer the heat to the outside environment, see Figure 4. This water circulation system can be flexible to connect with other applications, such as facility water or methods of waste heat re-use. The preparation of the microelectronics for this enclosure is described in the appendix.

2.1 Fluoro-organic dielectric liquid properties

The main problem of fully immersed, liquid-cooled microelectronics is the choice of liquid agent, which will be in direct contact with the electronic components. Though water a good choice from the heat transfer perspective, it is also a good electrical conductor and would damage the live circuitry.

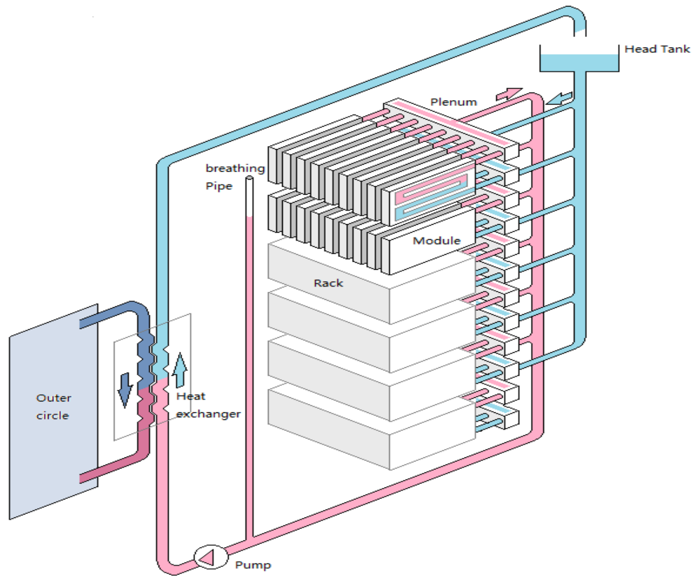

Figure 4 Schematic of the liquid-cooled system cabinet

The suitability of low viscosity dielectric liquids with large thermal expansivity for this task was demonstrated in Hopton and Summers [8]. Minerals oils, whilst having an appropriate dielectric strength, do not have the same propensity for natural convection for the task and would therefore need to be pumped. Mineral oils also have the drawback of being flammable.

In recent years a family of fluoro-organic liquids has been developed to replace the HCFC range of coolants [17] and they have been shown to possess the required properties for enclosed immersion of microelectronics [8].

2.2 Advantages of liquid-cooled systems

The main advantage of a direct liquid-cooled solution is the higher heat transfer capacity per unit. For the indirect liquid heat transfer, i.e. in the water jacket, the additional property of high conductivity, especially in a system with pure liquid-to-liquid heat exchange will have much lower temperature drops.

Table 1 compares the fluid properties of a fluoro-organic dielectric with that of water and air.

Property	Unit	Water	Air	Dielectric
Density	kg/m^3	997.0	1.18	1660
Specific heat capacity	J/(kg·K)	4182	1005	1140
Thermal Conductivity	W/(m·K)	0.6	0.025	0.069
Kinematic Viscosity(1)	cST	0.89	0.01568	0.71
Thermal Expansivity(1)	1/K	0.000257	0.0034	0.00145

Table 1 Thermal properties of coolants.
(1) : At 25^{o}C

In general, air has a very low density (about 1/1000 of water) and to carry a given quantity of heat (between two fixed temperatures) requires a large volume of air (ie high speed) rather than small volume of liquid (ie low speed). In some cases, such as density driven natural convection, the fluid velocity is very low and therefore liquid would be a better choice with a larger specific heat (per unit volume). Computational fluid dynamics simulations of the naturally convective flow inside the enclosed modules has identified that the fluid velocity is typically 5m/min.

Along with the significant thermal advantage, there are some other benefits of liquid-cooled solutions. A liquid-cooled data centre usually requires fewer fans and rotating components, therefore expending less energy and providing increased reliability due to fewer moving parts. In a fully immersed liquid-cooled solution the primary coolant is contained in a static (sealed) condition as shown earlier in Figure 3. A typical 500kW data centre with fully immersed liquid-cooled systems would require only 32 pumps instead of more than 1000 spinning fans in an equivalent air-cooled solution, and the noise level of a fully liquid-cooled approach is negligible.

Further benefits of a direct liquid-cooled data centre are that all the computer nodes will be inside a sealed container and in a fully controlled environment, which would have minimum level of dust and vibration. With the high heat capacity of liquids, there is also a large thermal inertia, which could be beneficial for power disruptions.

2.3 Disadvantages of liquid-cooled systems

Although direct liquid-cooled systems have the described benefits over other air-cool based systems, the major disadvantage is in ensuring liquid sealing and thus avoiding leakage problems. In most liquid-cooled designs the primary coolant is required to be pumped around the data centre. Leakage detection systems are required for safety of both personnel and equipment. In addition, understanding the pressure variations within a liquid system (typically +/-0.5 atmospheres gage) is important to ensure correct specification and management of pumps.

3. Methodology

This paper makes an energy and performance comparison between two data centre solutions, one based on advanced hybrid air-liquid cooled cabinets and the other using enclosed, immersed direct liquid-cooled system. The configuration and experimental data is acquired from two operational systems at the University of Leeds and the data is used later to construct 2 hypothetical equivalent systems to form a detailed comparison.

3.1 Air-water hybrid system and fully immersed liquid-cooled in the University of Leeds

Table 2 lists the details of the two operational systems at the University of Leeds. The enclosed, immersed, direct liquid-cooled computer server system was deployed in a laboratory environment at the University of Leeds (see Figure 6) in late 2012 and the analysis of the energy consumption for the immersed direct liquid cooled system is measured directly from the facility. The cooling configuration of the HPC systems at the University of Leeds (see Figure 5), which uses rear door liquid-loop heat exchangers connected to large scale chillers on the building roof, is adopted for comparison. Air-cooled system level measurements were conducted on a single server desktop apparatus.

Real system at University of Leeds	HPC systems, (Figure 5).	Immersed Direct liquid-cooled cabinet, (Figure 6).
Facility capacity (kW)	250	3
Computer system	Sun, HP and SGI blades	Dual socket SuperMicro
CPU	Mix of Intel/AMD	Mix of Intel / AMD
Rack cooling method	Mixture of passive and fan based active rear-door water cooled	Enclosed, immersed, direct liquid cooling (Iceotope Ltd)
External heat rejection	Airedale chillers with free cooling	Passive air cooled via domestic radiators

Table 2 Configurations of the HPC systems and the fully-immersed liquid-cooled system in the University of Leeds

Figure 5 Photo of part of the HPC system in the data centre at the University of Leeds [18].

Figure 6 Cabinet with the immersed liquid-cooled modules in a lab at the University of Leeds [16]

The system with immersed liquid-cooled modules at the University of Leeds is not a full cabinet as shown in Figure 6, on the other hand the university's HPC system is a complete data centre and combines a variety of old and new server nodes, so assumptions have been made in this work to scale the real facilities to construct 2 hypothetical systems with identical IT hardware, but using the two different cooling strategies.

Fabricated system	Air-water hybrid system	Fully immersed liquid-cooled system
Target facility Capacity (kW)	250	250
Computer system	SuperMicro X9D series	SuperMicro X9D series
CPU	Intel (E5-2670)	Intel (E5-2670)
Rack cooling method	back-door water cooled (based on Airedale OnRak™ 28kW)	Fully liquid cooled (based on Iceotope)
External heat rejection	Airedale chillers with free cooling	Airedale free cooling

Table 3 Hypothetical air-liquid hybrid system and fully immersed liquid-cooled system configuration.

In Table 3 the fully immersed liquid-cooled system has been scaled up to match the size of the University of Leeds HPC system, both hypothetical systems are assumed to use the same mother-board / CPU arrangement (SuperMicro X9D with Intel 2670 Xeons) and the Airedale Ultima Compact FreeCool chillers are included to complete the total energy calculation. With the above listed assumptions it is clear to see that the only physical difference between the 2 systems is in the in-rack cooling methods, which will ultimately be where the energy is saved.

Before comparing the 2 hypothetical systems listed in Table 3, a series of tests using the actual running systems are performed to provide the fundamental data for the energy calculations. Energy efficiency tests are performed with (i) the cabinet of direct liquid-cooled modules in the university (ii) a single node of the direct liquid-cooled system (node 107) was taken out and run in a single air-cooled rack to conduct the same energy efficiency test, but in air rather than the dielectric. The results form the 2 tests provide the basic temperature and energy efficiency data to build up the hypothetical direct liquid-cooled and hybrid air-cooled data centres.

3.2 Fully immersed liquid-cooled system test

To construct the hypothetical data centre based on immersed liquid-cooled systems requires energy efficiency results to be obtained from the running system. The primary configuration of the liquid-cooled system in Leeds University is outline in Table 4.

Name	Model	Number	Specification	Load
Power Distribution unit	Avocent PM3000	1	380V / 3 phase to 220C	Up to 22KW actual3KW total
Power Supply unit	Super Micro PWS-1K62P 1R	2	220V / 1 phase to 12V	1.6KW X2 = 3.2KW
Computer module	Iceotope Module	11	12V	Variable
Centre heated Pump	GRUNDFOS ALPHA2 L	1	2.6 m^3/h	
Radiator pump	Wilo Smart A-25/4-130	1	3.5 m^3/h	

Table 4 Fully immersed liquid-cooled system rack configuration

The configuration power and water distribution of the single cabinet containing the 11 immersed, direct liquid-cooled server modules is shown in the following schematic, Figure 7.

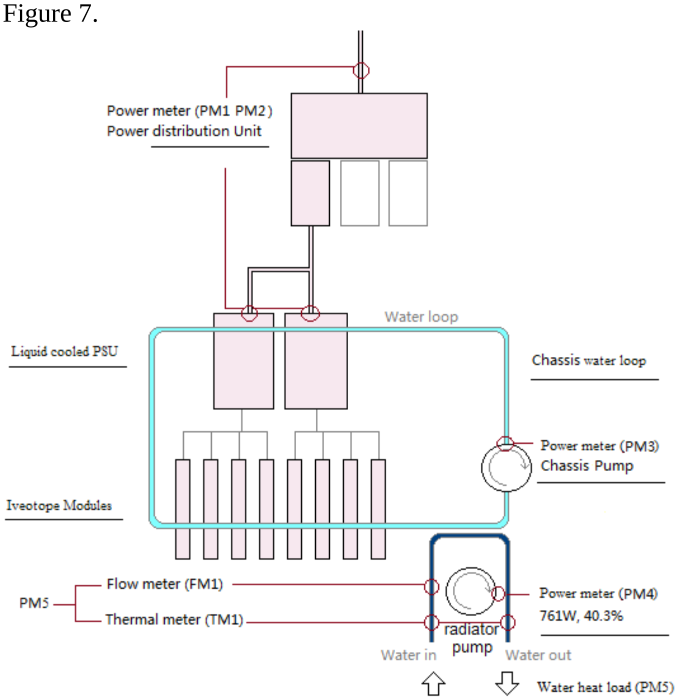

Figure 7 Schematic of power and water distribution.

Figure 8 indentifies a number power (PM), thermal (TM) and flow (FM) meters that are used to calculate the full system efficiency.

Table 5 in line with Figure 8 lists 6 readings that are required to evaluate the partial PUE of the system. Note that partial PUE is used here since the total facility power is based only on power distribution, cooling and the IT load. The values of PM1 and PM2 are available directly from the Avocent PM3000, and the temperature meter, TM1, actually measures the temperature difference since it has 2 thermal-couples that are connected to inlet and outlet. The 6 meters are monitored throughout the tests.

Name	output	Number	Specification	Model / other
PM1	W	1	Up to 3.2KW380V / 3 phase	Built in Avocent PM3000
PM2	W	2	220V / 1.6KW	
PM3	W	1		Model 2000MU-UK (L61AQ)
PM4	W	1		
FM1	m^3/h	1	Up to 12 l/min	N/A
TM1	^oC (ΔT)	2	Up to 80^oC	Center DT610B Thermometer

Table 5 Meter readings configuration of the fully immersed liquid-cooled system

With the temperature (TM1) and flow meter (FM1) values, the rate of energy transfer in the water system can be calculated based on specific heat capacity (SHC) of the water and the water density (ρ) to give a value for PM5 as,

$$PM5 = \frac{SHC \cdot FM1 \cdot TM1}{\rho} \quad (1)$$

The virtual power meter, PM5, which combines the values of FM1 and TM1, indicates how much of the cabinet heat is captured in the building water, which, in the case of the system at the university, is the amount thermal energy that is transferred to the domestic hot water radiators.

Table 6 tabulates how the meter readings yield the partial PUE, i.e. as the Total Facility Power / IT Load.

Name	Part	Terms
Total Facility Power	Complete system	PM1 +PM3 +PM4
IT Load	Iceotope Module (+PSU)	PM2 or (PM2 – PSU loss)
Partial PUE		(PM1 + PM3 +PM4) /PM2

Table 6 Partial PUE calculation

The partial PUE is realised by monitoring the 4 power meters during the tests and their values are shown in Tables 7 and 8 below. Table 9 shows the thermal status of the server modules during the tests. The system temperatures are monitored via their IPMI.

Table 7 tabulates the power meter values and their efficiency, which are read directly from the Avocent built-in monitoring. At the same time the other two power meter readings for the pumps are detailed in Table 8. Note: The AMD CPUs do not give a detailed temperature reading via the SuperMicro IPMI services; instead they only show thermal states as low, medium, high or overheated. Table 10 gives details of partial PUE and, using equation (1), PM5 calculations. The value PM2 indicates that 2128W of power is provided to the IT modules, but PM5 indicates that 761W is actually transferred to the secondary water circuit, that is in the case of the University facility, to the domestic hot water radiators.

Phase	Power	Efficiency
X	1076 W	97%
Y	1052W	96%
Total out (PM2)	2128 W	96.5%
Total in (PM1)	2205.1W	

Table 7 Fully immersed liquid-cooled system power load via PDU communication port

Pumps	Term	Name	Min power	Max power	Average
Rack water	PM3	Grundfos ALPA 2L - 15 -60	75W	85W	78W
Radiator	PM4	Wilo Smart A-25/4-130	16W	16W	16W
Total					94W

Table 8 Fully immersed liquid-cooled rack in the University of Leeds pumps power consumption

Module ID	System Temp	CPU1 /CPU2 Temperature	CPU-System ΔT	CPU1–CPU2 ΔT
101	53 °C	Medium	N/A	N/A
102	51 °C	79 °C / 76°C	25~27°C	2 °C
103	N/A	Medium	N/A	N/A
104	51 °C	70°C / 69°C	19~18°C	1 °C
105	52 °C	75°C / 69°C	22~16°C	6 °C
106	50 °C	Low / Low	N/A	N/A
107	53 °C	70°C / 69°C	18~16°C	2 °C
108	51 °C	71°C / 71°C	20~18°C	2°C
109	47 °C	Medium	N/A	N/A
110	46 °C	Medium	N/A	N/A
111	51 °C	73°C / 69°C	20~17°C	3 °C

Table 9 Fully immersed liquid-cooled system temperature reading via IPMIView

Partial PUE calculation (PM1 + PM3 + PM4) / PM2				
PM1	PM2	PM3	PM4	Partial PUE
2205.1 W	2128 W	78W	16W	1.081
External water loop heat load (PM5) calculation				
FM1	Inlet temp	Outlet temp	ΔT (TM1)	
110 l/min	32 °C	38 °C	6 °C	
Water SHC	Water density		Calculated PM5	
4178 J/(kg.°C)	994.1kg/m3		761W	

Table 10 Iceotope cabinet at the University of Leeds external water loop data

3.3 Advanced hybrid air/water-cooled system tests

In constructing the second system based on air cooling, the temperature difference of the major component (CPU temperature and system) that a single air-cooled computer node is required. An experiment was set up to monitor the inlet and outlet temperatures, and the air flow rate to obtain typical temperature increases over the inlet temperature for the main components. To capture a realistic outflow temperature, the outlet air was funneled into a duct with an exhaust diameter of 75mm and a length of 400mm. This was found sufficient to characterize the outlet temperature from a single measurement. The mean velocity was calculated by taking a series of measurements across the pipe diameter, and thus calculating the mean airflow.

A single 2U rack chasis node (SuperMicroCSE-217HQ-R1K62MB [20]) with single motherboard has been used to conduct this test The server unit is actually converted from one of the fully immersed liquid-cooled systems (ID: 107 in Table 9) (SuperMicro X9D with 2 Intel Xeon E5-2670 cores) and enables direct comparison of the two cooling methodologies. The tests make use of 2 software tools to load the server (StressLinux and LinPack) at close to 100% load, which should be ideally close to the operating condition of an HPC data centre under full performance. This resulted in a total energy load reading of 305W, which does not include the server fans as these are powered externally.

Temperature and velocity readings were taken at a range of points over the diameter of the exhaust pipe and are shown in Table 11. These readings became stable after 2 hours of continuous running.

Location	Velocity	Temp	Area of concentric rings
Mm	m/s	°C	m^2
Inlet	0.5	23.8	
Radial distance			
30	2.2	34.3	0.00083939
25	4.7	36.2	0.00051051
20	4.9	36.7	0.00047124
15	4.8	36.8	0.00043197
10	4.9	37	0.0003927
5	5	37	0.00035343
(Centre) 0	5.3	37	0.00141863
Average (based on area)	4.45	36.34	

Table 11 Velocity and temperature readings of the outlet from the air-cooled rack.

The key temperatures are listed in Table 12 and are based on the values in Table 11, the IPMI readings and a thermometer.

Location	Temperature °C	Device
Inlet / Ambient	23.8	Thermometer
CPU 1	69	IPMI
CPU2	70	IPMI
CPU average	69.5	
System	36	IPMI
Temperature delta (inlet to outlet)	12.54	
Temperature delta (inlet to CPU)	47.7	

Table 7 Temperature reading via IPMI View and thermometer

From Table 12, the temperature delta from the inlet to the outlet is 12.54°C. Under the exhaust conditions of 37°C the air density, ρ, is approximately 1.138kg/m^3, and the mass flow rate, $\dot{m}$, of the outlet can be calculated as,

$$\dot{m} = \rho \times A \times \bar{v}$$

where A is the surface area of the outlet, 0.004418m^2, and $\bar{v}$ is the averaged air velocity of the outlet, 4.45 m/s, as indicated in Table 11. The result is that the mass flow rate is $\dot{m}$=0.02237kg/s.

The average specific heat capacity (*SHC*) of air between inlet at 25°C and outlet at 37°C is approximately 1005 J/(kg·°C), and since the delta temperature from the inlet to outlet, ΔT, is 12.54°C the total heat flux Q that is released into the air would be,

$$Q = \dot{m} \times SHC \times \Delta T$$

yielding a value of Q of 282W, which is close to the system power of 305W and heat loss through the server chasis is expected.

3.4 Hypothetical systems configuration

The hypothetical air-liquid hybrid system in this work is based on the SuperMicro 2U rack design (CSE-217HQ-R1K62MB) [20], which contains 4 1U mother-boards inside a 2U package as depicted in Figure 8. In this configuration there is an N+N redundant PSU layout for each computer node, and 4 computer boards towards 1+1 PSU.

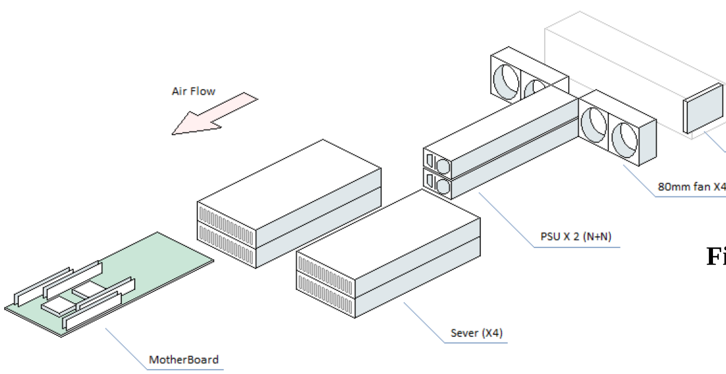

Figure 8 2U Air-water hybrid system computer / PSU node layout

The hypothetical fully immersed liquid-cooled system is based on the enclosed, immersed, direct liquid-cooled servers with 8 computer nodes and 2+2 PSU nodes in each rack level as demonstrated in Figure 9.

Although the air-water hybrid system and fully immersed liquid-cooled system have different layouts, they have the same computer node to PSU ratio (4:1), which from the power point of view gives them identical topologies for the energy efficiency calculations. The front view of the server nodes and power supplies is shown for both system configurations in Figure 10, which also indicates the cabinet space requirements for each solution. With the immersed, direct liquid-cooled system, servers are loaded in both the front and the back of the cabinet.

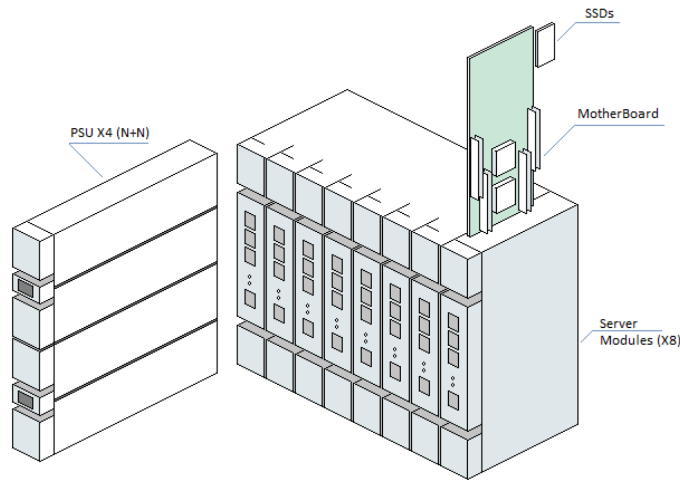

Figure 9 Hypothetical fully immersed liquid-cooled system computer / PSU node layout

The set up of the 2 hypothetical systems will lead to identical total computing performance, based on the same mother-boards and power consumption. They can be directly comparable and the difference between them would, as expected, be only due to the cooling efficiency at the different levels (IT level, cabinet level and facility level).

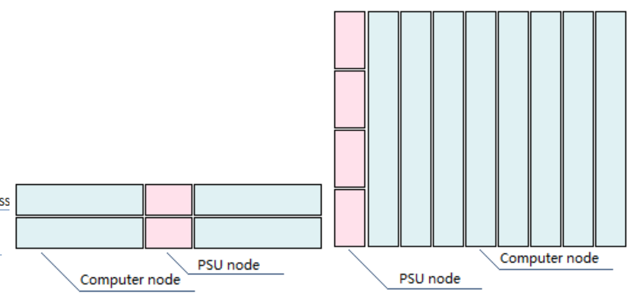

Figure 10 Front view layouts of air-water hybrid system chassis (left) and immersed direct liquid-cooled system chassis (right).

4. Result

The full set of calculated results for the two hypothetical systems are detailed in Table 13 for a target of 250kW of total power consumption for both air-water cooled hybrid and fully immersed liquid-cooled solutions.

From Table 13 it can be seen that the fully immersed liquid-cooled solution is able to achieve a partial PUE of around 1.14 at full load, compared to an equivalent air-water hybrid system, which has a PUE of 1.48. However this is based on the assumption that the computer systems are fully loaded and that for the hybrid air-water cooled systems, chiller free cooling is not used, which is a worst case scenario.

Usually most air-conditionings / chillers have an EER (Energy Efficiency Ratio) of around 3.0 under fully loaded conditions, which results in the partial PUE of the data centre that is at least 1.33 when the chiller is operating at 100% mechanical load. The HPC data centre at the University of

Leeds has systems running near to peak load and is consuming approximate 100kW of cooling power to manage a 250kW system load, which yields a partial PUE of 1.4.

	Type	Unit	Load	Number	Hybrid air-water cooled power consumption	Liquid-cool power consumption
Server / IT level	SuperMicro System	X9DTT / Intel Xeon E5-2670 X2	305W	48×14 = 672	204.96kW	204.96kW
	Cooling Fans	Nidec V80E12BS2	23.4W	48×14 = 672	15.72kW	N/A
	Storage	Intel SSD 330	0.85W	48×14 = 672	0.571kW	0.571kW
	PSU Fan	Nidec R40W12BGCA	15.8W	24×14=336 168 active	2.65kW	
	PSU loss	Super Micro PWS-1K62	7% loss	24×14=336 168 active	15.67kW	14.43kW
				Theoretical performance	166×2 GFLOPS 223.1TFLOPS	166×2 GFLOPS 223.1TFLOPS
				Total load	223.91kW	206.27kW
				GFLOPS/W	996.4	1081.6
Cabinet level	Cabinet fan	Airedale LogiCool OnRak LOR6042U-C028-0	161W	14	2.254kW	N/A
	Pump	GrundFos Alpha 2L	45W	2×14=28 14 active	N/A	0.63kW
	Telco Equipment	D-Link DGS-1210-48	33.4W	2×14=28	0.935kW	0.935kW
	PDU	Avocent PM3000	3.5% loss	2×14=28	7.84kW	7.84kW
				component	11.03kW	8.78kW
				Total load	234.94kW	215.05kW
Total Facility Power	UPS	APC Symmetra PX 250kW	4% loss	2	9.40kW	8.60kW
	Chiller	Airedale Ultima Compact Chiller UCFC250D-8/2	EER=3.03 Chiller on	2	77.54kW	N/A
			EER=19.3 Chiller off	2	N/A	11.14kW
	Ventilation (CRAH)	Airedale AlpaCoolDF25A / CUS8.5	880W	10	8.8kW	N/A
				component	95.73kW	19.74kW
				Total load	330.67kW	234.80kW
				Total PUE	1.477	1.138
				MFLOPS/W	674.7	950.2
				Total cooling power	98.17kW	11.77kW
				Power saving		95.88kW

Table 8 Overall power data of a hybrid water/air-cooled data centre compared to one based on enclosed, immersed direct liquid-cooled server technology [21-29]

It is also possible to directly compare the Performance Per Watt (PPW) of these 2 hypothetical systems since they contain identical computing hardware. From Table 12, the air-cooled system is rated to 674.7 MFLOPS/W which is close to the 10th (Tianhe-1A) in the 2012 green 500 data centres, while the liquid-cooled system is rated at 950 MFLOPS/W close to the 4th (RIKEN AICS) in the same ranking list [12].

One reason why the immersed direct liquid-cooled systems avoid using mechanical cooling, as indentified in Table 13, is due to the higher efficiency of the direct thermal coupling with liquid-to-liquid heat exchangers and the systems' higher operating temperature as highlighted in Table 14.

From Table 14 it can also be seen that the hybrid air-water cooled solution has a maximum delta temperature that is 18^{o}C greater than that of the solutions based on immersed direct liquid-cooled systems, which is the reason why the chillers are assumed to be operating in mechanical cooling mode to deal with the additional cooling requirements.

	Air-cooled system			Liquid-cooled system		
	medium	Temperature		medium	Temperature	
		In	out		In	out
Ambient	Air		25°C	Air		25°C
Chiller	R407c/ water	25°C	20°C	Water	38°C	32°C
Building water	Water	20°C	22°C	Water	32°C	38°C
Ventilation	Air / water		24°C			N/a
Rack	Air	24°C	36°C	Water	33°C	39°C
Computer node	Air		36°C	Water	33°C	39°C
				Dielectric		53°C
CPU	Air		70°C	Dielectric		70°C
Max delta temperature	CPU to Chiller			CPU to Ambient		
	63°C			45°C		

Table 9 Temperature stack-up data of an air-cooled data centre compares to a liquid-cooled data centre

5. Conclusion

This work has compared the energy efficiency between a data centre based on an advanced hybrid air-water cooling solution with a data centre that uses enclosed, immersed, direct liquid-cooled modules. The analysis has been completed under a number of assumptions, which include; the IT systems are operating at full load and the supply and return temperatures of the facility water being elevated such that the air-cooled solution requires full mechanical cooling. Usually both liquid-cooled and air-cooled data centre would have completely different designs and hardware configurations, which arguably makes direct comparison difficult in practice.

The data centre based on the hybrid air-water cooled systems is calculated to operate with a partial PUE of 1.48. This is compared with the enclosed, immersed, direct liquid-cooled based data centre, which is calculated to operate at a partial PUE of 1.14 – 34% more efficient. Comparing the PPW values based a theoretical linpack performance yields a value for the hybrid air-water cooled system of 621.86MFLOPS/W, which can be compared to the fully immersed liquid-cooled based system of 875.79MFLOPS/W – 40.8% better performance than the hybrid air-water system. Finally the data centre based on enclosed, immersed, direct liquid-cooled systems, under certain assumptions, consumes 95.88kW less power, which saves 29% of the total power and up to 88% of cooling power over the hybrid air-water cooled system.

Acknowledgments

The authors are grateful for the financial support from Iceotope Research and Development Ltd. The University of Leeds Iceotope installation was funded by the University's Digital Innovation Research Hub.

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Appendix

The server modules in the University of Leeds system built by Iceotope Ltd are based on commodity microelectronics. The microelectronics are not modified, but the procedure in constructing the Iceotope modules involves;

1. Removal of the on-board battery from the mother-board. Since the battery is a sealed unit, it might have sealing issues that interfere with the liquid-cooled system.
2. Liquid tight cabling and signal ports are adopted. Careful engineering redesign is required for all of the signal transfer ports (such as USB, Ethernet, PCI-E, infiniband, etc.). All of these ports transfer electronic signals from the liquid immersed microelectronics to the outside with no liquid leakage or signal loss.
3. Standard heat sinks for all of the microprocessors (CPUs, North Bridge, etc.) are replaced with profiles that suit the liquid-cooled environment and are optimally designed for optimum heat transfer.