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Performance analysis of new liquid cooling topology and its impact on data centres

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Abstract

A large amount of the energy consumed by data centres is related to the cooling demand. The use of optimised liquid cooling technology enables one to increase the water inlet temperature and the water temperature difference of a data centre. Accordingly, the energy consumption of the data centre infrastructure can be reduced by appropriately utilising free cooling available on-site. This paper presents an experimental investigation and performance analysis conducted on a novel liquid-cooled topology deployed within OVHcloud data centres. A rack cooling system based on a combination of close-coupled cooling and direct-to-chip cooling is presented. The experimental setup used comprised five information-technology racks with operational servers under different temperature profiles (15 K and 20 K) for two thermal conditions (27 °C and 35 °C). The results indicated a repartitioning of thermal load absorption between close coupled cooling and direct-to-chip cooling to approximately 56% and 44 %, respectively. Thereby, air was still necessary as a coolant for the data centre. A temperature difference was validated for all the information technology racks, whereas the 20 K temperature-difference profile was validated with the proposed new rear-door heat exchanger (RDHX) configuration. In addition, a performance analysis was performed on a data centre of 600 kW cooled with this topology for three heat rejection systems (mechanical cooling system using chillers, indirect free cooling with evaporative cooling, and hybrid chillers with intelligent dry coolers) under four climatic conditions. Indirect free cooling combined with an evaporative cooling system showed optimal energy savings. A reduction in annual power consumption by 89 % was achieved compared with the mechanical cooling system at four locations where data centres were located. The cooling partial power usage effectiveness of data centre was reduced by at least 16 % with respect to mechanical cooling. An increase in the temperature difference of the information technology racks from 15 K to 20 K caused a reduction in the water usage effectiveness of the data centre by at least 40 %. An increase in the temperature of the cold water supplied to the data centre by 5 K caused a reduction in water usage effectiveness and annual water consumption by at least 30 % and 47%, respectively.

Keywords: Data centre cooling, free cooling, liquid cooling, energy, heat transfer

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36 1. Introduction

37 Cloud computing and data centres (DCs) have become valuable parts of our lives because of many vital
38 internet-scale facilities such as internet-wide search, email services, and artificial intelligence. The use of
39 DCs has been increasing exponentially. Consequently, their energy consumption and environmental
40 impact have become progressively more significant. The energy costs of DCs increase by 1 % every five
41 years, as presented by Buyya et al. [1]. The most recent statistical studies presented by Kamiya et
42 Kvarnström [2] estimated that DCs worldwide consumed approximately 200 TW-h in 2018. This
43 accounted for 1 % of the electricity consumption worldwide. The electricity consumption in a DC
44 repartition shows that 44 % is consumed by the DC information technology (IT) equipment; 40 % by the
45 cooling system; and 16 % by the electrical power distribution, UPS, lighting, and other service-building
46 usage [3]. The cooling systems in DCs account for the largest portion of the total electricity consumption
47 after IT equipment. Thus, there is a vital need to address environmental issues by ensuring the use of
48 cooling systems with low power consumption for DCs. The power usage effectiveness (PUE) is a measure
49 of the efficiency with which a DC consumes power. It is defined as the ratio of the total DC power
50 consumption to the computing-equipment power consumption. The ideal PUE is 1.0.

51 It is high priority to reduce the power consumption of DC cooling systems through optimised thermal
52 management techniques [4,5]. Two key cooling-solutions have been developed over the past years: air
53 cooling and liquid cooling. Air-cooled DCs have several constraints [6,7]. The convective heat transfer
54 coefficient of air is low because of its poor thermal properties. Furthermore, the difficulty of achieving
55 an appropriate airflow control system and the absence of a system to achieve it in certain DCs presented
56 by Dai et al. [8] resulted in the mixing of heat dissipated from IT equipment with the cold air supplied.
57 This caused hot spots around and inside the racks. The circulation of hot air that exhausts from the rack
58 outlet into the cold air stream supplied to rack inlets by a computer room air handler (CRAH) causes IT
59 equipment to underperform, malfunction, or fail completely. The DC environment needs to be
60 overcooled to cool these hot spots efficiently. However, certain servers may still receive inadequate
61 cooling. Thus, the mixing of warm and cool airstreams, reliance on air as a heat transfer medium, and
62 power consumption of cooling hardware cause air cooling systems to be ineffective. Liquid-cooled water
63 systems can support high-intensity power and have a wide range of advantages.

64 At present, two main water liquid cooling techniques are used to cool DCs: close-coupled cooling and
65 direct liquid cooling (see Table 1). Thermal resistance can be reduced dramatically using water liquid
66 cooling solutions. Water has a heat-carrying capacity (approximately 3.3 times higher than that of air).
67 CPUs and GPUs are the equipment on a server that consumes the most energy. Thus, liquid cooling via
68 direct-to-chip cooling has been demonstrated to be an efficient technology because the water
69 temperature returning from IT equipment of DCs is significantly higher than that typically observed in
70 closely coupled cooling systems [9]. Zimmermann et al. [10] demonstrated that a differential
71 temperature of 15 K between the chip and coolant was sufficient for chip cooling using water as a
72 coolant in the IBM BladeCenter Chassis. Ljungdahl et al. verified that the coolant temperature has a
73 direct impact on energy savings and cooling efficiency [11]. Coles et Greenberg [12] demonstrated that
74 direct-to-chip cooling achieves a significant decrease in the total DC site energy-consumption (by 14–20
75 %).

Liquid cooling solutions	Description
--------------------------	-------------

Close coupled cooling	In-row Cooling [7]	<ul style="list-style-type: none"> • Row-based air conditioning units are installed inside the rack rows. • Airflows interact with the ambient room environment (Open-loop solution). • Typical inlet water temperature = 12–23 °C
	In-rack Cooling [13]	<ul style="list-style-type: none"> • The cooling system is combined with the server rack, and both are sealed completely. • No interaction with the ambient room environment (Closed-loop solution) • Typical inlet water temperature = 12–23 °C
	Rear Door Heat Exchanger [14,15]	<ul style="list-style-type: none"> • This type of solution is based on a combination of fans and a finned heat exchanger installed on the rear side of racks. • Airflows interact with the ambient room environment (Open-loop solution). • Typical inlet water temperature = 12–23 °C
Direct-to-chip cooling	Cold plates [16]	<ul style="list-style-type: none"> • A heat sink with micro-channels (cold plates) is in direct contact with IT components of the DC, such as CPUs and GPUs. Here, the water flowing across absorbs chip energy. • Typical inlet water temperature 27–45 °C

76 Table 1. Data-centre water liquid cooling solutions.

77 Recently, many researchers focused on the evaluation of optimised cooling technologies for energy
78 savings and reduction of environmental impact. Zhang et al. [17] performed a comprehensive literature
79 review of the cooling technologies for DCs. They concluded that a combination of multiple cooling
80 technologies including direct-to-chip liquid cooling could be a future trend to further improve the energy
81 efficiency of DCs. It was also indicated that the use of these energy-saving cooling technologies could
82 help achieve average energy-savings of up to 50% compared with the conventional mechanical cooling.
83 Udakeri et al. [18] indicated that liquid cooling and air cooling could be highly efficient when combined
84 as a hybrid cooling strategy for DCs.

85 The DC market is oriented towards cloud computing, which involves more hard disks and RAMs. In this
86 case, full cooling via cold plates is not feasible, and standard air-cooling solutions would still be required.
87 A combination of close-coupled cooling (rear-door heat exchanger (RDHX)) and direct-to-chip cooling
88 could be used. The rear side of a server rack is equipped with an RDHX. This eliminates the need to
89 separate the hot/cold aisle [15]. The output water from the RDHX is reused as inlet water for the direct-
90 to-chip liquid cooling system. Therefore, a higher DC water temperature difference (ΔT) can be
91 achieved. This enables more extensive heat reuse [19] or the capability to reject this heat to the
92 atmosphere with a dry cooler. This, in turn, eliminates the need for a cooling tower or chiller plant in
93 most climates [20]. The workload of heat rejection systems used to evacuate heat to the external
94 environment can be reduced significantly by appropriately utilising on-site available free cooling [21–
95 23]. Evaporative cooling (EC) can be used as a pre-cooler in environments where the ambient
96 temperatures of dry coolers are higher than the temperature of the liquid cooling supplied [24–26].

97 Different evaporative cooling systems can be employed to cool the inlet air [27]. These include
98 evaporative cooling pads, which have been demonstrated to be effective [28,29].

99 This work focused on an experimental study to develop and validate a novel cooling topology for IT racks
100 that is based on liquid cooling deployed within OVHcloud DCs. The paper is structured into six sections.
101 Section 2 describes the cooling system topology. Section 3 presents an experimental bench designed
102 and constructed to study and characterise this cooling topology at the rack level through tests
103 conducted on five racks equipped with different profiles of IT equipment. In addition, the section
104 describes tests performed on different configurations of RDHX to determine the best configuration to
105 operate the DC under two thermal conditions (TC-27 °C and TC-35 °C) while preventing overheating,
106 throttling, and equipment damage. Section 4 describes the integration of this cooling topology within a
107 DC of 600 kW and its coupling with three heat-rejection systems (a mechanical cooling system using
108 chillers, indirect free cooling with evaporative cooling, and hybrid chillers with integrated intelligent dry
109 coolers) under four climatic conditions. Section 5 describes an investigation of the impact of the water-
110 temperature profile in terms of partial power usage effectiveness and water usage effectiveness for a
111 DC cooled with indirect free cooling using an EC pad through two approaches: rack temperature
112 difference (Section 5.1) and increase in DC water inlet temperature (Section 5.2). Finally, in Section 6,
113 the conclusion outlines the important results of this study.

114 2. Cooling system topology

115 OVHcloud is a French-based cloud computing company that offers VPS-and OpenStack-based public
116 clouds. Their DCs are cooled via a liquid cooling system using an indirect free cooling technique (IFC).
117 The technique is based on heat recovery from the servers using water pumped by a pumping substation
118 (PSS) to direct chip heat sinks (also called water blocks (WBs)) and heat exchangers placed inside racks.

119 Figure 1 shows the scales of the key OVHcloud cooling system bricks. Four orders of magnitude are
120 presented in decreasing order: heat rejection system (dry cooler) > PSS > rack RDHX and cooling
121 distribution unit (CDU) > server WB. Cold water is pumped to the rack using PSS, heated by the rack's IT
122 equipment, and cooled again by dry coolers installed outside the DC.

123

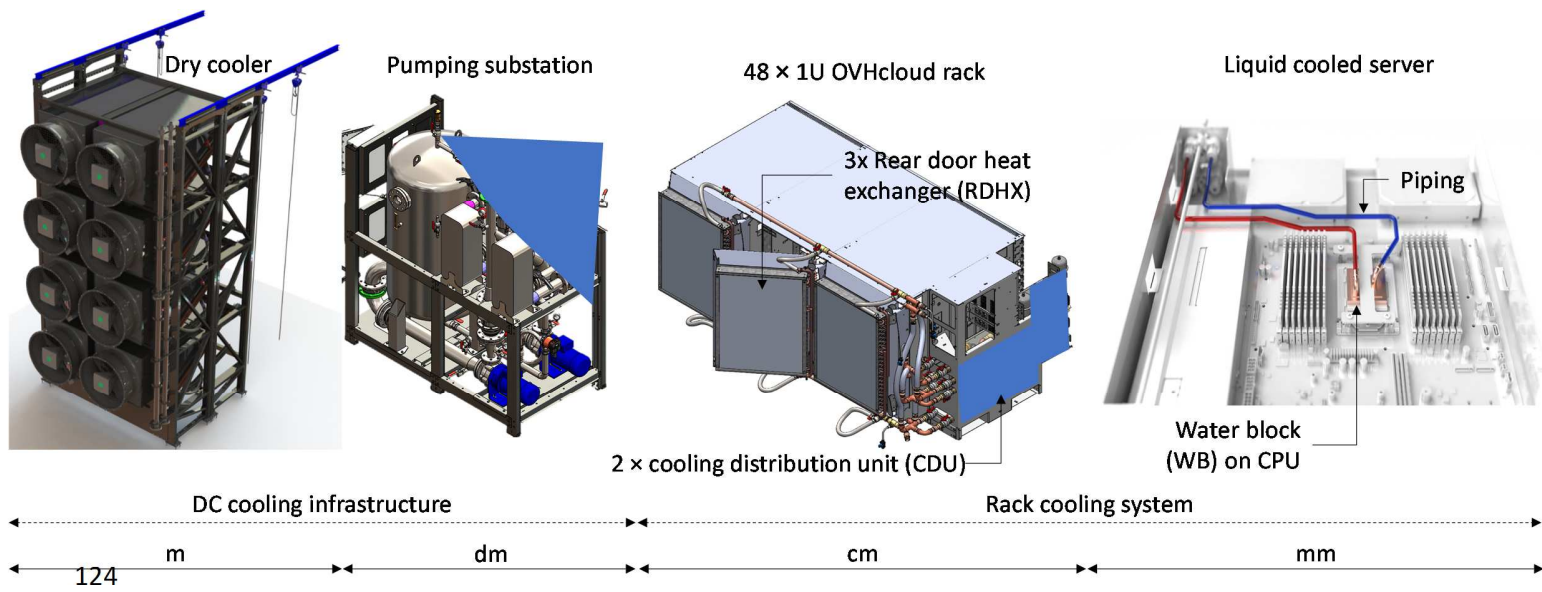


Figure 1. Scale of the cooling system studied.

Figure 2(a) shows the main elements of the system: the rack cooling system, PSS, and dry cooler. The rack cooling system is based on a combination of air and liquid cooling. It consists of RDHEXs and WBs with air/water cooling capacity (AC/WC). The water temperature is to be maintained at 27 °C for maintaining the inlet air temperature of the server and the inlet water temperature of the WB at 30 °C and 40 °C, respectively. Moisture condensation inside the DCs is prevented by operating these at the recommended temperature and humidity levels. The condensation that occurs inside IT equipment of servers causes short circuits, thereby risking the entire DC operation. Furthermore, condensation promotes corrosion and limits the lifetime of IT equipment. Table 2 lists the recommended temperature levels inside the OVHcloud DCs. The preferable temperature level is between 20 and 35 °C (green area), wherein condensation and IT equipment overheating risks are zero. The orange area includes two ranges based on the risk characteristic: 15–20 °C (where condensation is likely) and 35–40 °C (where the lifetime of IT equipment can be impacted). The DCs must be prevented from operating in the orange area. Operation in the red areas (< 15 °C and > 40 °C) is prohibited to prevent condensation and overheating risks, respectively.

Green utilisation area	Orange utilisation area	Red utilisation area
20 °C < T < 35 °C	15 °C < T < 20 °C 35 °C < T < 40 °C	T < 15 °C and T > 40 °C

Table 2. Conditions of indoor ambient temperature of DC for operating OVHcloud IT racks.

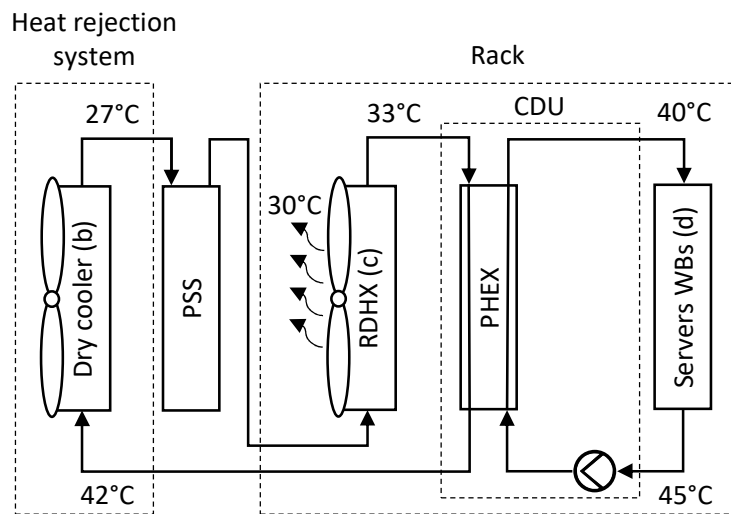
The rack current cooling system is based on a temperature difference of 15 K between the inlet and outlet of the water manifolds. As shown in Figure 2(a), water enters the RDHX at 27 °C and exits at 33 °C after absorbing the heat generated by the air-cooled IT equipment. Then, it passes through the CDU's Plate Heat Exchanger (PHEX). Finally, it recovers the heat absorbed by the WBs and exits the rack at 42 °C. Accordingly, the heat rejection system must cool the water from 42 °C to 27 °C.

146 An RDHX is a combination of fans and a finned heat exchanger installed on the rear side of the racks (see
147 Figure 2(c)). The IT equipment apart from CPUs and GPUs are cooled by the RDHX. Each rack contains
148 three rear doors. Each door is mounted on an ensemble of 16 servers called a console. Each door has 12
149 ebm-papst fans [1] (nominal electrical power of 4.6 W and maximal rotation speed of 3300 rpm). The
150 fans of the rear door suck cold air from the rack's front cold side to cool the IT equipment on the
151 servers, such as motherboards, RAM, and hard disks. The air flowing through the servers crosses the
152 RDHX and is cooled again. Accordingly, the hot aisle is contained completely inside the rack, with both
153 circulation aisles in front and behind the rack being cold.

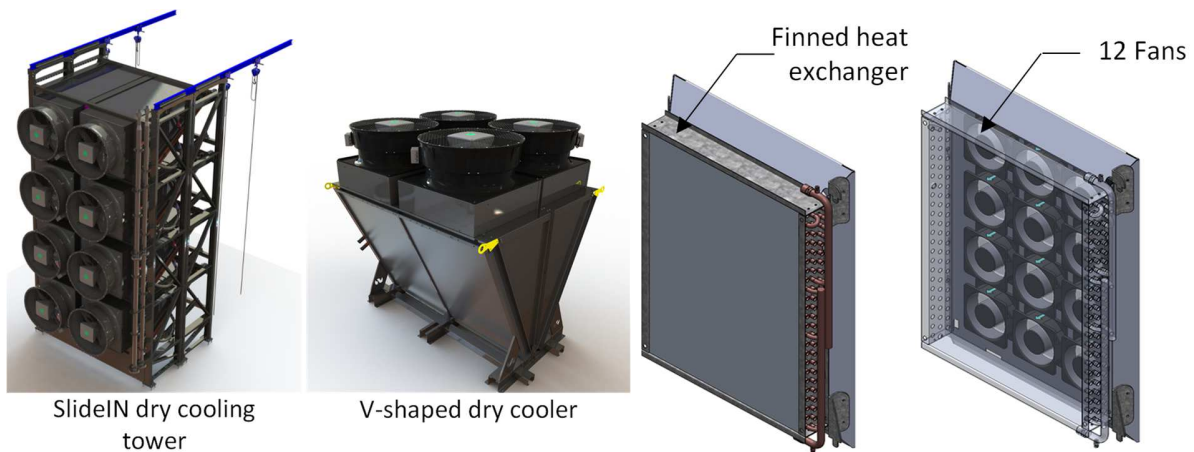
154 The CPUs and GPUs are liquid-cooled using direct-to-chip cold plates with water as the coolant. The cold
155 plate is called WB. It is a heat sink with channels (see Figure 2(d)), where water flows across and absorbs
156 chip energy. WBs are fed with cold water by CDUs integrated inside the rack via a piping network. Two
157 CDUs are installed in parallel to ensure redundant water pumping. The CDU is composed of a pump
158 (maximum electrical power = 60 W) and plate heat exchanger (PHEX). The facility water entering the
159 rack flows directly through the three RDHXs that cool the hot air. Then, it flows through the CDUs of the
160 rack.

161 The PSS ensures the pumping of water to the racks. It is designed with a water storage tank and two
162 redundant pumps to maximise the system availability. It provides up to 650 kW of cooling capacity to
163 support up to 65 racks with a 10 kW load density. In addition, it contains two PHEXs for heat recovery
164 and additional backup cooling system options. It has a small footprint of 2000 × 1000 mm. Thereby, it
165 can be deployed conveniently irrespective of whether it is positioned next to the IT enclosures or
166 outside the DC.

167 The dry coolers (or dry cooling towers) shown in Figure 2(b) play an important role in the DC cooling
168 systems. External air is used to cool the liquid pumped around different cooling components installed in
169 the DC without applying a refrigeration process. Depending on the external climatic conditions, dry
170 coolers are used alternatively to cool the water supplied to the fan coils. Two types of dry coolers are
171 used: a SlideIN cooling tower and V-shaped dry coolers (see Figure 2(b)). The SlideIN cooling tower is
172 composed of four finned heat exchangers and eight ebm-papst AxiBlade variable-speed fans [30]
173 (maximum electrical power of 2880 W each, and maximum rotation speed of 1000 rpm). A V-shaped dry
174 cooler is a light-structure dry cooler composed of two finned heat exchangers and four fans (identical to
175 those of the SlideIN cooling tower). That is, a SlideIN cooling tower is equivalent in cooling capacity to
176 two V-shaped dry coolers.



(a)



(b)

(c)

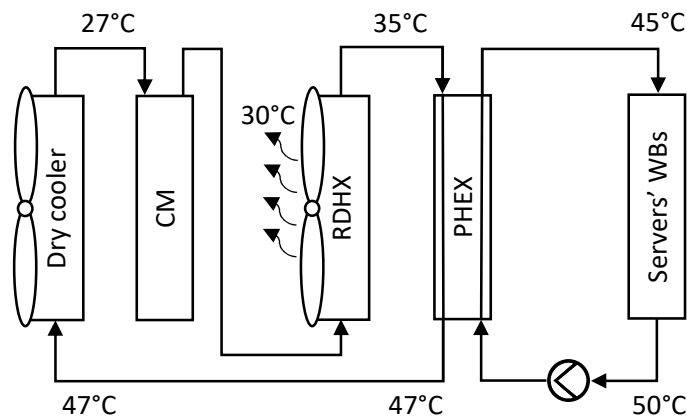


(d)

Figure 2. (a) Global OVHcloud cooling system topology; (b) Different types of dry coolers; (c) Rear Door Heat Exchanger (RDHX); (d) Different types of WB-channel geometries.

186 **3. Experimental investigation of rack level**

187 An increase in the temperature difference in the racks causes a decrease in the flow rate of water
188 supplied per rack. Thus, an increase in the temperature difference permits a higher heat load per
189 pumping unit for an equivalent PSS hydraulic capacity. The dry cooler performance is likely to be
190 enhanced significantly because water would enter higher levels, whereas fans and EC water
191 consumption per IT kW would be reduced. Accordingly, the footprint (kW/m²), DC infrastructure capital
192 expenditure (CAPEX), DC operating expense (OPEX), PUE, and water usage effectiveness (WUE) would
193 increase significantly when the heat load per PSS and dry cooler is higher. An alternative temperature
194 profile (to that presented in Figure 2(a)) was studied. Here, the temperature difference increases from
195 15 K to 20 K, water flow rate increases marginally, and dry-cooler cooling capacity attains 600 kW rather
196 than 400 kW. In this case, water enters the RDHX at a temperature of 27 °C and exits at 35 °C. It absorbs
197 the heat generated by the air-cooled IT equipment, passes through the CDU while recovering the heat
198 dissipated by the WBs, and exits the rack at 47 °C (see Figure 3). Accordingly, the water would be cooled
199 from 47 °C to 27 °C using a dry cooler. A rack test bench was designed and constructed within OVHcloud
200 Experimental DC in Croix-France to validate the direct impact of temperature difference (15 K and 20 K)
201 on operational IT racks.



202
203 **Figure 3. Topology of 20 K cooling system**

204
205 **3.1. Experimental setup**

206 Figure 4(a) shows the rack test bench. A climatic chamber characterised by an insulated 20 ft maritime
207 container was used to control the boundary conditions (ambient temperature and relative humidity) of
208 the tested rack.

209 Figure 4(c) shows the hydraulic circuit of the climatic chamber. Two PSS are used: PSS-2 is the main DC
210 PSS, and PSS1 is connected to it via a high-accuracy solenoid valve to supply water to the rack test
211 bench. The solenoid valve was equipped with a temperature probe installed at the climatic chamber
212 water inlet to ensure smooth regulation of the supplied temperature. Figure 4(d) shows the distribution
213 of sensors in the system. A thermocouple was installed inside the climatic chamber to measure the

214 global air temperature. The internal and external wall temperatures of the climatic chamber were
 215 measured using several thermocouples installed on the walls, as well as the external ambient
 216 temperature. The system heat load and leakage were estimated accordingly. The temperature, pressure,
 217 differential pressure, and flow rate sensors were located at various positions including the inlet and
 218 outlet of each component (RDHX, PHEX, and WB servers). The details of the sensors are specified in
 219 Appendix A. It provides a detailed description of their location, suppliers, and measurement range.

220 The heat load is estimated as follows:

$$Q = \dot{m} C_p \Delta T \quad (1)$$

221 where \dot{m} (kg/s) is the water flow rate, C_p (kJ/kg/°C) is the specific heat of water, and ΔT (°C) is the water
 222 temperature difference in the circuit.

223 The absolute pressure sensors, differential pressure sensors, thermocouples, and flow rate sensor were
 224 calibrated by comparing the response measured by each component to those measured by high-
 225 precision sensor probes. The uncertainties were evaluated using the method described by Kline and
 226 McClintock [31]. For example, the uncertainty of the thermal heat load was evaluated by

$$\frac{\Delta Q}{Q} = \sqrt{\left(\frac{\Delta \dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta T_1}{T_2 - T_1}\right)^2 + \left(\frac{\Delta T_2}{T_2 - T_1}\right)^2} \quad (2)$$

227 where Δ signifies the uncertainty. T_1 and T_2 are the inlet and outlet temperatures, respectively.

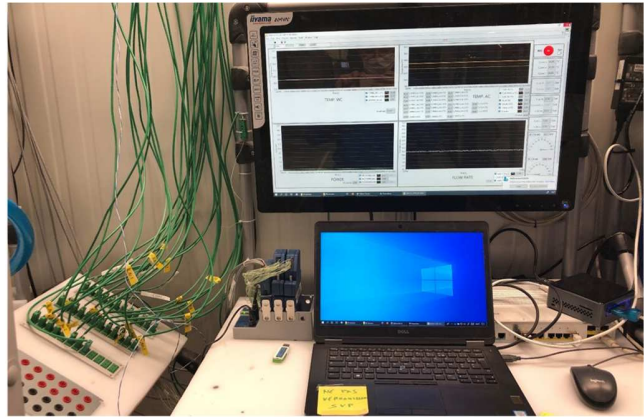
228 Table 3 shows the uncertainties for different parameters involved in the measurements.

Parameter	Uncertainty
Temperature, T (°C)	±0.210 °C
Pressure, P (Pa)	±0.5 %
Differential pressure, ΔP (Pa)	±0.25 %
Flow rate, \dot{m} (l/min)	±4 ml/min
Relative humidity, RH (%)	±2 %
Heat load, Q (W)	±1.4 %
Locations and distances (m)	±1 %
Response time (s)	±5 %

229 Table 3. Uncertainties for different parameters involved in the experimental tests.

230 The temperature sensors were type-K thermocouples with an accuracy of ±0.210 °C after the calibration
 231 process. The National Instruments data acquisition system NI cDAQ-9174 is a compact DAQ system. It
 232 was used to record all the temperatures, pressures, and flow rates throughout each experimental test
 233 (see Figure 4(b)). Then, the data were read, processed, and stored using a program running in LabView
 234 with a frequency of one measure per second [32]. In addition, the solenoid valve was controlled
 235 remotely by a Carel controller.

236

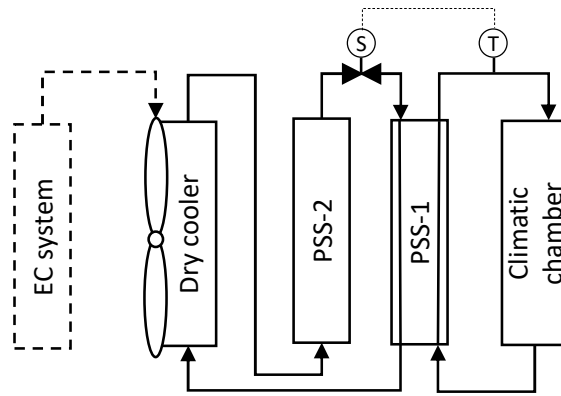


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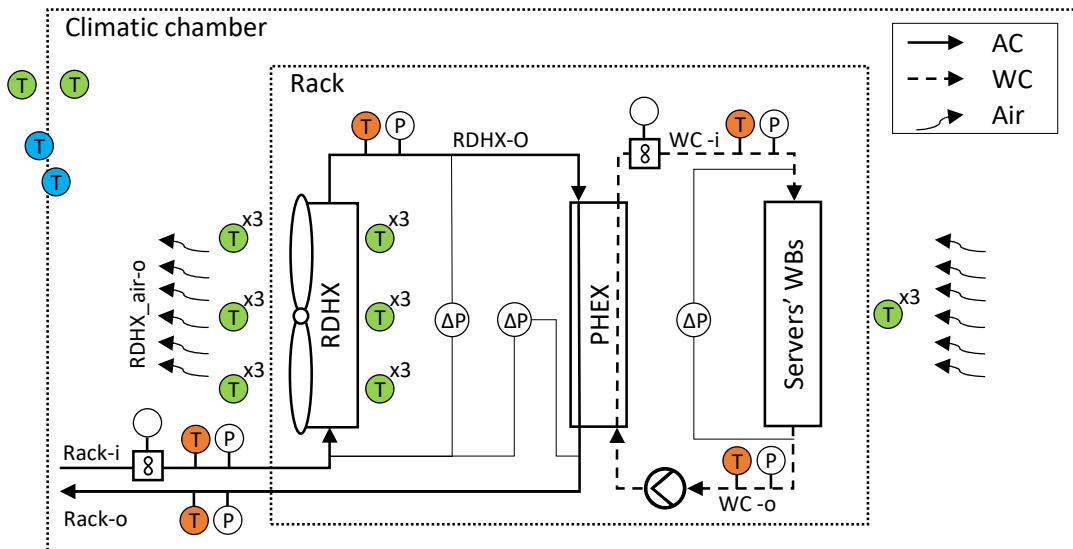
238

(a)

(b)



(c)



(d)

239 Figure 4. (a) Rack test bench; (b) Acquisition system; (c) and (d) Schematic representation of test facility
240 and experimental setup, respectively.

241 Before starting the tests, the experimental loop including the rack AC and WC circuits was filled
242 completely with water. Then, air was vented from high points to ensure that the entire circuit was free
243 of air. The rack-supplied flow rate was adjusted manually depending on the required rack load and
244 temperature difference. The water temperature supplied to the rack was controlled via the solenoid
245 valve to attain the boundary conditions effectively. Moreover, the WC flow rate was adjusted directly in
246 the CDUs. A flexible I/O (fio) script was used to stress the memory components of servers such as hard
247 disks. CPUs and RAMs were stressed in conjunction using a script that allocates a quantity of RAM to
248 each logical core of the CPUs to be used by a memtester process. Forty eight and 24 servers were
249 stressed while testing 1U servers and 2U servers, respectively. Different temperature measurements of
250 the intelligent platform management interface (IPMI) on the servers were also collected. Different IT
251 equipment such as CPUs, GPUs, RAMs, and motherboards were analysed during each test. Other tools
252 such as the Intel® Performance Counter Monitor and AMD uProf were used to assess the stability of
253 server performance under different thermal conditions applied.

254 Tests were conducted to analyse the impact of water conditions (temperature differences of 15 and 20
255 K, and the water inlet temperature) on the performance of the racks. Globally, IT racks within OVHcloud
256 DCs operate under the nominal thermal conditions of 27 °C (TC-27). First, a 15 kW rack composed of 24
257 × 2U servers (Rack -1) was considered under two thermal conditions (inlet water temperatures of 27 °C
258 and 35 °C). Moreover, six RDHXs configurations having a higher cooling power corresponding to
259 different numbers of rows and circuits (named A, B, C, D, E, and F; A is the most frequently used in
260 OVHcloud DCs with a temperature difference of 15 K) were considered. The RDHXs have an equal
261 surface area with a fixed fin thickness and spacing. Their tube size and fin spacing are the minimum that
262 can be achieved with respect to each console's power for 12 fans and its fabrication technology.
263 Additional rows per RDHX enhance the heat exchange area and heat transfer coefficient. This reduces
264 the pinch and increases the air pressure drop and thereby, affects the rack's thermal performance as the
265 airflow rate is reduced significantly. This, in turn, affects the turbulence and heat transfer efficiency to
266 cause rack overheating. Thus, a combination of optimal rows and circuits is required to optimise the
267 performance. Referring to Table 2 and to prevent DC and rack overheating, the RDHX pinch was set
268 below a limit value ($Pinch_{max}$) of 7 K. The RDHX power should be increased if this value exceeds the
269 operating conditions. RDHX pinch is defined as

$$Pinch = T_{RDHX_air-o} - T_{Rack-i} \quad (3)$$

270 where T_{RDHX_air-o} and T_{Rack-i} are the outlet air temperature of RDHX and inlet water temperature of
271 rack, respectively.

272 3.2. Results and discussion

273 Table 4 shows the performance of Rack-1 under temperature differences of 15 K and 20 K for the six
274 RDHX configurations. For RDHX A, the rack was validated under a temperature difference of 15 K. This
275 was because its pinch is below the maximal value, whereas it exceeds the limit value at 20 K. For other

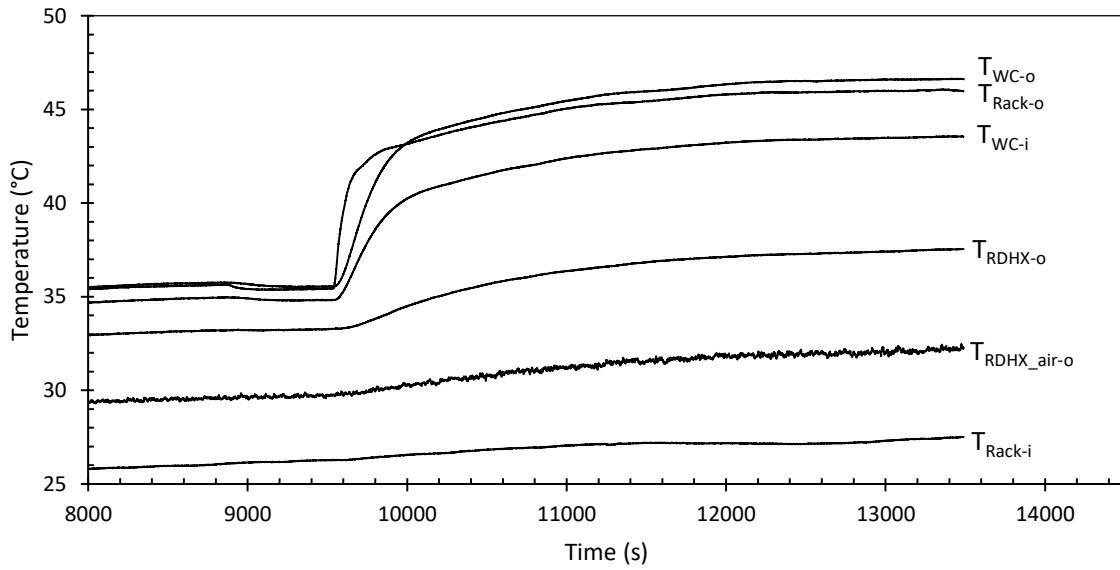
276 RDHX configurations and under TC-35, the rack behaviour was satisfactory and did not display
 277 overheating, throttling, or equipment damage. In addition, the rack was operated with significantly high
 278 performance without reduction in the CPU frequencies or memory bandwidth throughout the 2 h of
 279 each test.

AC/WC (%)	Condition	RDHX	T_{Rack-i} (°C)	T_{Rack-o} (°C)	ΔT (K)	Pinch (K)
54/46	TC-27	A	27.74	42.49	14.75	5.98
55/45	TC-27	A	27.84	47.93	20.09	8.53
57/43	TC-35	A	34.89	54.60	19.71	8.34
56/44	TC-35	B	35.80	56.60	20.80	3.42
57/43	TC-35	C	35.05	55.08	20.03	4.93
57/43	TC-35	D	35.05	55.97	20.92	4.01
57/43	TC-35	E	35.20	56	20.8	3.98
57/43	TC-35	F	34.78	55.11	20.33	3.89

280 Table 4. Thermal hydraulic behaviour of Rack-1.

281 Table 4 also lists the values of the ratio of air cooling capacity to water cooling capacity (percentage)
 282 within the rack. RDHX A is generally used with an AC/WC ratio of 30/70 % for old server profiles,
 283 wherein CPUs account for a substantial portion of the electrical consumption. With new server profiles
 284 filled with RAMs and hard disks, tests were switched to incremented row values (configurations B, C, D,
 285 E, and F). This ensured higher AC capacities. Thus, the AC/WC ratio of 30/70 % was no longer valid.
 286 Equilibrium was observed with an optimal pinch of 3.42 K in the RDHX B configuration for an AC/WC
 287 ratio of 56/44 %. These results show that air is still required as a coolant in addition to a water-cooling
 288 solution in cloud computing applications.

289 Figure 5 shows the transient thermal behaviour of the rack using RDHX B under TC-27. Initially, the rack
 290 was in standby mode. When the fio and/or memtester scripts were launched at $t = 9500$ s, the rack's
 291 water circuit temperature started to increase to achieve thermal equilibrium after 1 h of operation. The
 292 inlet (T_{WC-i}) and outlet (T_{WC-o}) temperatures were stabilised at 43.6 and 47.1 °C, respectively.
 293 Furthermore, the rack's water inlet (T_{Rack-i}) and outlet (T_{Rack-o}) temperatures were stabilised at 27.4 and
 294 46.8 °C, respectively. The RDHX air outlet temperature ($T_{RDHX-air-o}$) was stabilised at 32 °C. The servers
 295 showed stable and satisfactory results for all their components (RAMs, CPUs, and hard disks).



296

297 Figure 5. Transient thermal behaviour of Rack-1 using RDHX B under nominal condition (TC-27).

298 Work conducted on Rack-1 was repeated on four additional racks representative of the ones observed in
 299 the worldwide market to examine their performance with RDHX B. Table 5 shows the performance of
 300 the five racks under an inlet water temperature of 35 °C (TC-35) and a water temperature difference of
 301 20 K. All the racks showed an unbalanced AC/WC ratio between 45/55 % and 58/42 %. The exception
 302 was Rack-5 (which contained additional water-cooled GPUs) with a ratio of 37/63 %.

Rack	Q (kW)	AC/WC (%)	T_{Rack-i} (°C)	T_{Rack-o} (°C)	ΔT (K)	Pinch (K)
1	15.28	56/44	35.80	56.60	20.80	3.42
2	20.66	54/46	35.35	54.39	19.04	3.84
3	13.47	45/55	35.20	54.94	19.74	3.55
4	14.19	58/42	34.96	54.81	19.85	4.48
5	27.86	37/63	34.84	56.65	21.80	4.86

303 Table 5. Behaviour of OVHcloud IT racks under inlet water temperature of rack of 35 °C.

304 The results showed that a temperature difference profile of 20 K was ensured for all the IT racks with
 305 different electrical powers. Thereby, an identical water outlet temperature was attained for all the
 306 racks. This enables convenient deployment within the DC infrastructure. With a high-water inlet
 307 temperature to the DC (up to 35 °C), condensation risk is eliminated and a long lifetime of IT equipment
 308 is insured. Besides, a 20 K temperature difference leads to a high-water outlet temperature from the DC
 309 making the free cooling solution more effective and enhancing energy saving.

310 This liquid cooling system was demonstrated to be efficient with a 20 K temperature-difference profile.
 311 The next section presents an analysis of the impact of this temperature difference on DC performance,
 312 and its comparison with the 15 K profile using three heat rejection systems under four climatic
 313 conditions.

314 **4. Coupling of the new topology with different heat rejection systems**

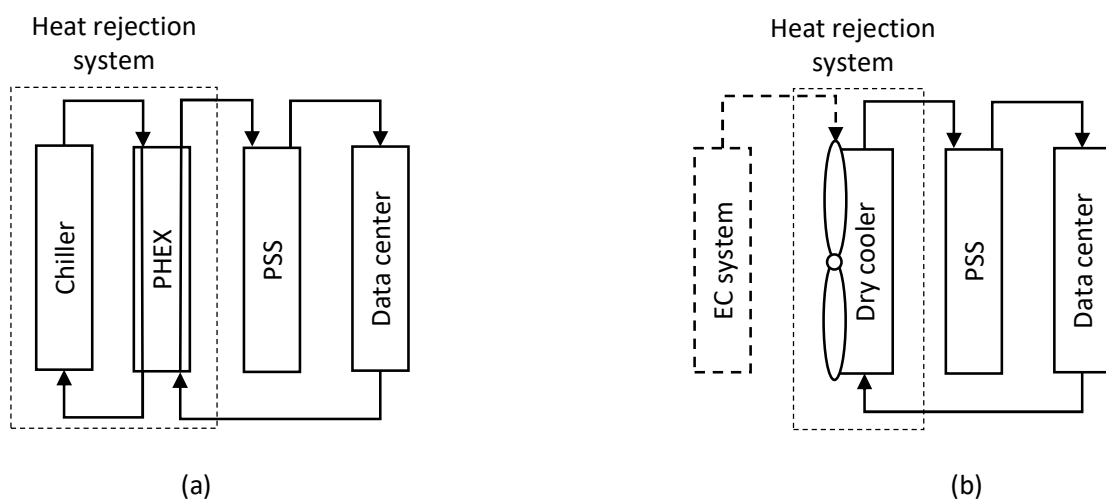
315 Different heat rejection systems could be used to discharge the heat of a DC to the environment. In this
316 section, an energy analysis of three cooling systems is presented (mechanical cooling system with
317 chillers, indirect free cooling, and hybrid chillers with integrated intelligent dry coolers). The objective is
318 to demonstrate that the IFC can achieve optimal energy savings.

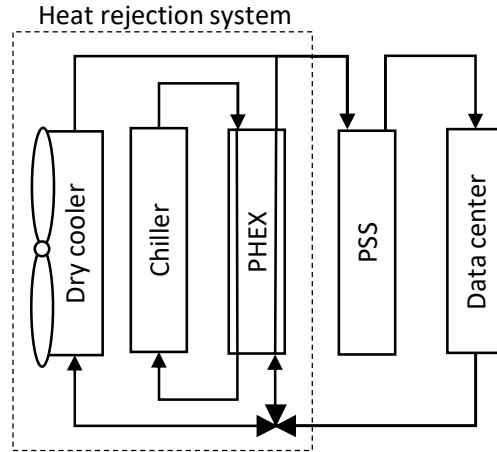
319 A mechanical cooling (MC) concept includes a chiller to transfer DC heat to the outdoors with a PSS,
320 which circulates hot water from the DC to a PHEX thermally linked to the chiller (see Figure 6(a)). Water
321 from the DC is cooled using a chiller equipped with a pumping system that circuits the glycol water
322 between the chiller and PHEX. The chiller is installed on a secondary circuit to protect it from the high
323 temperatures provided by the DC, which causes high-pressure build-up. The compressor, condenser
324 fans, and pump are the active components of the chiller and consume energy. However, the high
325 electricity consumption of the chiller compressors causes chilled-water systems to incur the highest
326 capital cost of DC power.

327 Indirect free cooling (IFC) systems are driven by circulating cold water directly to cool a DC. The IFC
328 concept involves the use of dry coolers as a heat rejection system with the DC isolated completely from
329 its ambience. The principle of heat transfer from the coolant and its discharge to the environment is
330 realised by air-to-water finned heat exchangers. When the sum of the outside air temperature and heat
331 exchanger pinch exceeds the cold-water temperature to be returned to the DC, an EC system is
332 employed to precool the outside air before cooling the fins (see Figure 6(b)).

333 A hybrid system is a combination of the MC and IFC systems (MC + IFC), as shown in Figure 6(c). It
334 operates in two modes based on the outside temperature. The system operates under the MC mode at
335 high outside temperatures. At low outside temperatures, the chiller is bypassed using a three-way valve,
336 and the system operates in the IFC mode. This enables the DC to utilise free cooling.

337





(c)

Figure 6. Configurations of heat rejection system: (a) chiller (MC); (b) indirect free cooling system (IFC); (c) hybrid cooling (IFC + MC)

4.1 Performance metrics

Performance metrics play an important role in operating DCs with high energy-efficiency, reliability, and low total cost of ownership (TOC). Thus, it is vital to obtain the highest computational output from the input energy of DCs. The green grid introduces two metrics (power usage effectiveness (PUE) and water usage effectiveness (WUE)) to measure the energy efficiency of DCs [33]. The PUE is defined as

$$PUE = \frac{P_{Cooling} + P_{Electrical} + P_{IT}}{P_{IT}} \quad (4)$$

where $P_{Cooling}$ is the electrical power consumed by the cooling system. $P_{Electrical}$ includes the power lost in the energy distribution system through line loss and other UPS infrastructure, and the electrical power used to support spaces and light in the DC. P_{IT} denotes the total power consumed by the rack for computing, storage, and network equipment. A low PUE (approaching one) indicates that most of the energy consumed by the DC is used for computing.

The metric called partial power usage effectiveness (PPUE) defines a certain portion of the overall PUE of a DC within a clearly defined boundary. The infrastructure-cooling PPUE is defined as follows:

$$PPUE = \frac{P_{Cooling} + P_{IT}}{P_{IT}} \quad (5)$$

Table 6 shows the active equipment consuming energy on the cooling line-up, which is composed of a SlideIN cooling tower (or two V-shaped dry coolers) and PSS. The $P_{Cooling}$ in $PPUE$ is the sum of the consumptions of the infrastructure cooling equipment.

Element	Quantity during operation	Maximum power	Total maximum power
Dry cooler fans	8	2.88 kW	23.04 kW
Substation pumps	1	2.71 kW	2.71 kW

359 Table 6. Maximal power consumption of infrastructure cooling system.

360 WUE is defined as

$$WUE = \frac{\text{Annual site water usage}}{P_{IT}} \quad (6)$$

361 The annual water usage of a site includes the water used for humidification and that evaporated on-site
362 for the energy production or cooling of a DC and its support systems. It is a sustainability metric that
363 measures the amount of water used by DCs to cool IT equipment.

364 The electrical power consumption of each heat rejection system depends on the external conditions of
365 the DC. It is defined in this study as a function of the external temperature. For example, to provide a
366 reasonable water-return temperature of DC, the speed of the dry cooler fans increases with the external
367 temperature. This increases the power consumption.

368 The total power consumption under the MC concept is defined as the sum of the power consumption of
369 the substation pumps (one over two) and that of the chiller:

$$P_{MC} = \sum_{i=1}^m P_{PSS\ pumps-i} + \sum_{i=1}^n P_{Chiller-i} \quad (7)$$

370 where P is the power consumption. m and n are constants representing the numbers of substation
371 pumps and chillers, respectively, installed in the DC infrastructure. Note that the power consumption of
372 a chiller includes those of its compressor and pumps, which are provided by the manufacturer.

373 The total power consumption of an IFC cooling system is defined as the sum of the power consumed by
374 the substation pumps, EC pumps, and dry cooler fans:

$$P_{IFC+EC} = \sum_{i=1}^m P_{PSS\ pumps-i} + \sum_{i=1}^o P_{Dry\ cooler-i} + \sum_{i=1}^p P_{EC\ pumps-i} \quad (8)$$

375 where o and p are constants that represent the numbers of dry coolers and EC pumps, respectively,
376 installed in the DC infrastructure.

377 The total power consumption of a hybrid cooling mode (MC + IFC) is defined as the sum of the power
378 consumed by the substation pumps, chillers, and dry cooler fans:

$$P_{MC+IFC} = \sum_{i=1}^m P_{PSS\ pumps-i} + \sum_{i=1}^n P_{Chiller-i} + \sum_{i=1}^o P_{Dry\ cooler-i} \quad (9)$$

379 An approach similar to that used in prior studies was adopted for the power consumption of the dry
 380 cooler fan [34]. Fan affinity laws indicate that the power consumed by a fan increases cubically with the
 381 airflow rate (\dot{V}):

$$Fan\ Power \propto (\dot{V})^3 \quad (10)$$

382 The methodology for calculating the power consumption of the dry cooler is presented in Appendix A
 383 (Figure 11). The airflow rate, pressure drop, and outlet air temperature are provided by the
 384 manufacturer of the heat exchanger based on the outdoor conditions. This enables the selection of the
 385 fan. The power consumption of a fan is determined based on the physical parameters at fan's operating
 386 point:

$$P_W = \sum_{i=0}^3 a_i \dot{v}^i \quad (11)$$

387 where i and a_i are constants. \dot{V} is the airflow rate (m^3/h) generated by the fans.

388 The water consumption of the EC used in the IFC system was calculated as a function of the water
 389 demand of the EC system using cooling pads. It is determined based on the technical data provided by
 390 the manufacturer regarding the airflow rate, external air temperature, and humidity conditions. It is
 391 defined as the sum of evaporated water and bleed-off quantities required per hour to operate a dry
 392 cooler equipped with an EC system. In addition, WUE can be extracted as the total quantity of water
 393 required per kWh. The methodology for calculating WUE is presented in Appendix A (Figure 12).

394 4.2 Performance analysis under different climatic conditions

395 The performance of free cooling is affected strongly by the climatic zone [35]. Therefore, four sites
 396 worldwide with different climates were investigated for a DC portion of 600 kW: Mumbai (India),
 397 Singapore, VintHill (USA), and Roubaix (France). Temperature and relative humidity data of the past 40
 398 years were collected from the weather underground community site [36] and analysed (one record
 399 every 30 min). The warmest year in the 40 years for each location was selected. Table 7 shows the
 400 selected cities and their average climatic conditions during that year.

City	Elevation (m)	Warmest year	Temperature (°C)		Relative humidity (%)
			Wet bulb	Dry bulb	
Mumbai	14	2018	28.85	23.47	64.64
Singapore	15	2018	28.50	25.25	77.45
VintHill	125	2019	14.35	11.34	73.04
Roubaix	33	2018	11.53	8.80	76.16

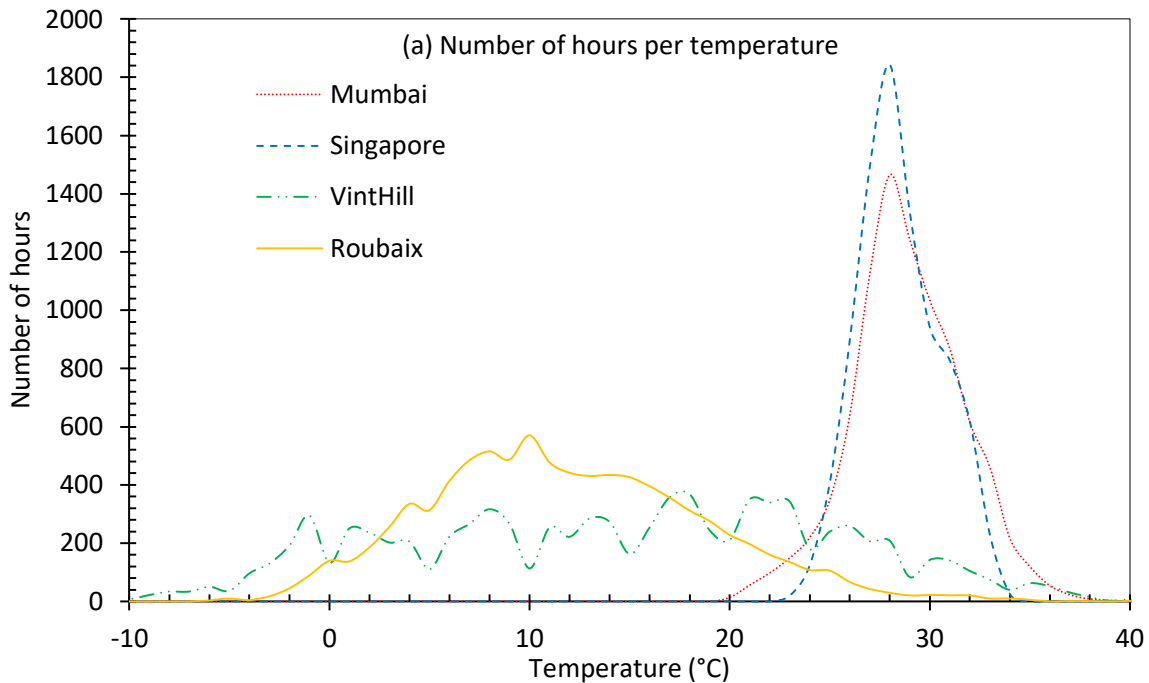
401 Table 7. Average climatic condition during the warmest year in Mumbai, Singapore, VintHill, and Roubaix
 402 in the 40 years.

403 Figure 7(a) shows the temperature frequency in hours per year for the climatic data of each location.
404 The key hours for Mumbai and Singapore are between 25 and 35 °C, whereas these are distributed
405 between -2 °C and 30 °C for VintHill and between 5 and 20 °C for Roubaix.

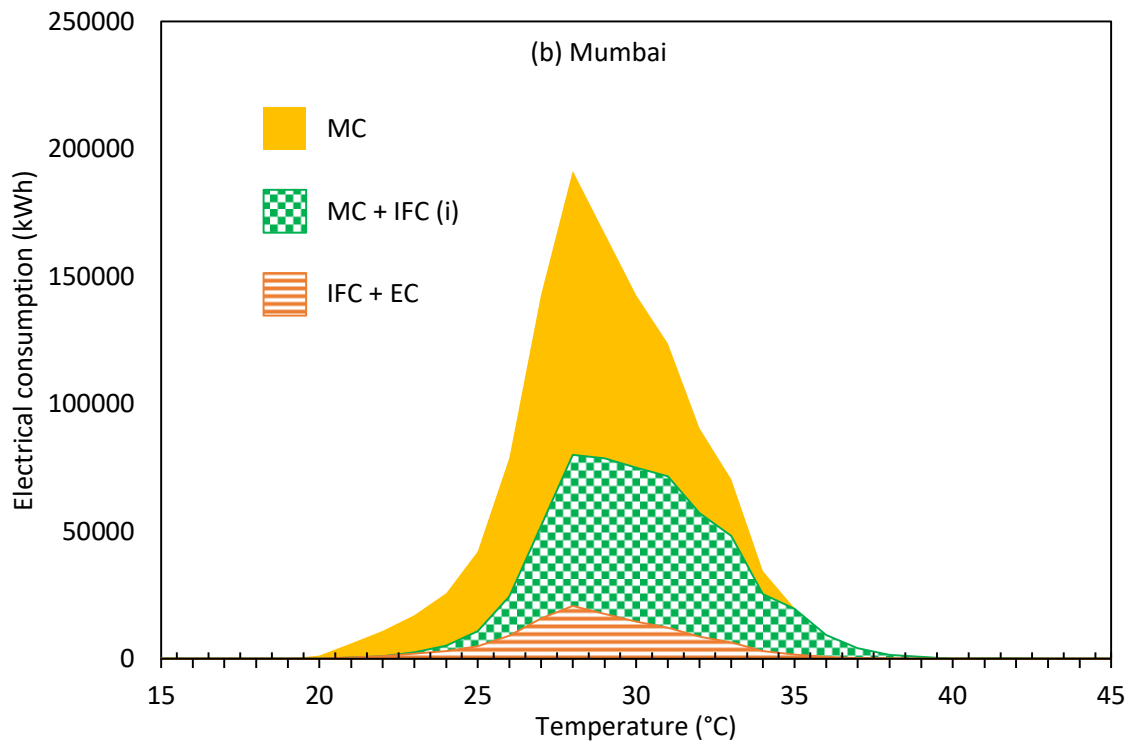
406 Figure 7(b), (c), (d), and (e) show the electricity consumption of the DC cooling system with respect to
407 the external temperature of DC in Mumbai, Singapore, VintHill, and Roubaix, respectively, for the three
408 heat rejection systems shown in Figure 6. The results show that the cooling systems require higher levels
409 of cooling in Mumbai (Figure 7(b)) and Singapore (Figure 7(c)) than in VintHill (Figure 7(d)) and Roubaix
410 (Figure 7(e)).

411 The addition of a dry cooler to the chiller (hybrid mode: MC + IFC) reduced the average electrical
412 consumption by 51.8, 54.8, 82.4, and 92.8 % compared with the MC system, for Mumbai, Singapore,
413 VintHill, and Roubaix, respectively. The MC + IFC system can save energy significantly. Herein, the
414 electricity consumption is limited to dry cooler fans and pumps, whereas the active components of the
415 chiller are idle. Because the IFC system is more directly influenced by the external conditions, the impact
416 of the addition of a dry cooler to the chiller in Roubaix and VintHill (where the outside temperatures are
417 low) is more significant than that observed for Mumbai and Singapore.

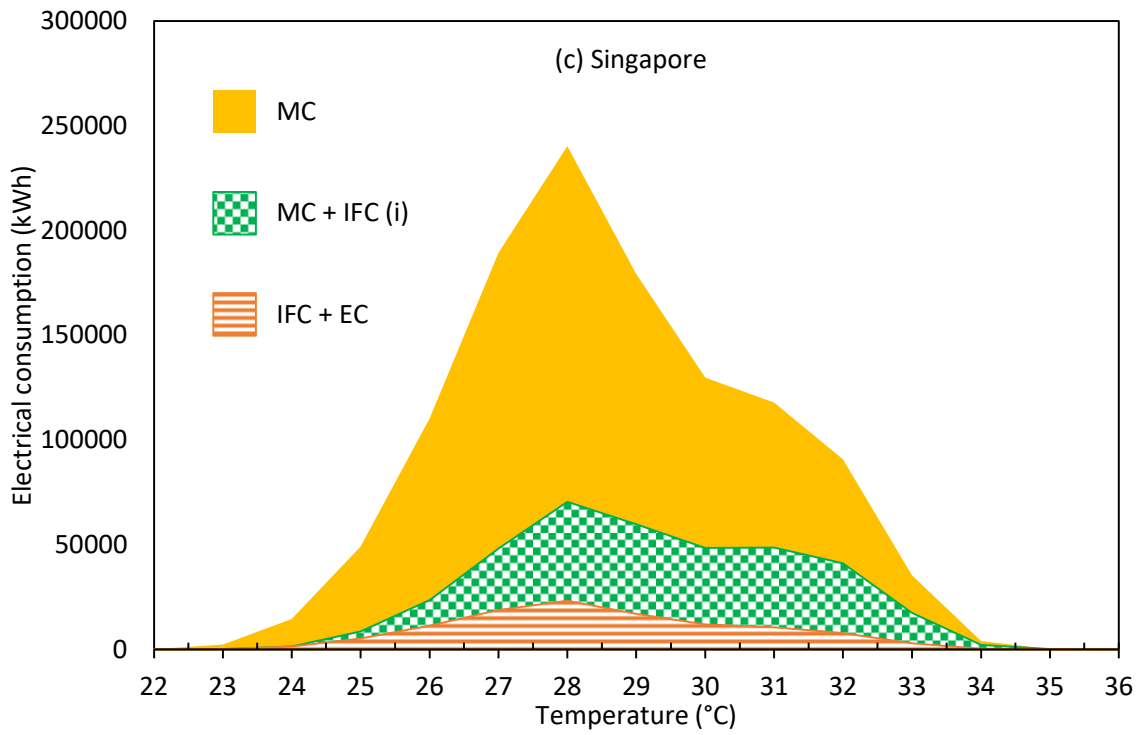
418 The use of an IFC equipped with an EC (IFC + EC) reduces the electrical consumption by 89.5, 89.3, 93.25,
419 and 94.95 % compared with the MC system, for Mumbai, Singapore, VintHill, and Roubaix, respectively.
420 The IFC + EC system shows optimal energy savings. Herein, a reduction in power consumption of at least
421 89 % could be achieved in all the four locations by restricting the electrical consumption to the dry
422 cooler fans and substation pumps. For Singapore, the water temperature exceeded 27 °C by less than 2
423 °C. This is reasonable for rack operation under TC-35, as described in Section 3.2.



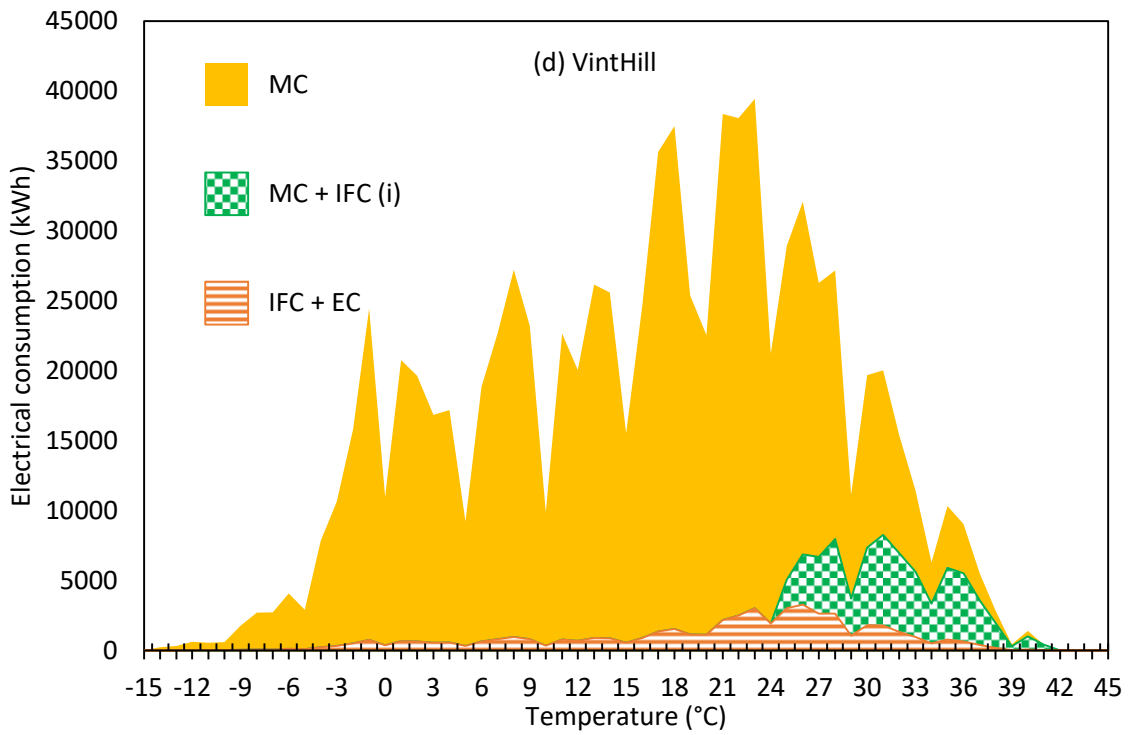
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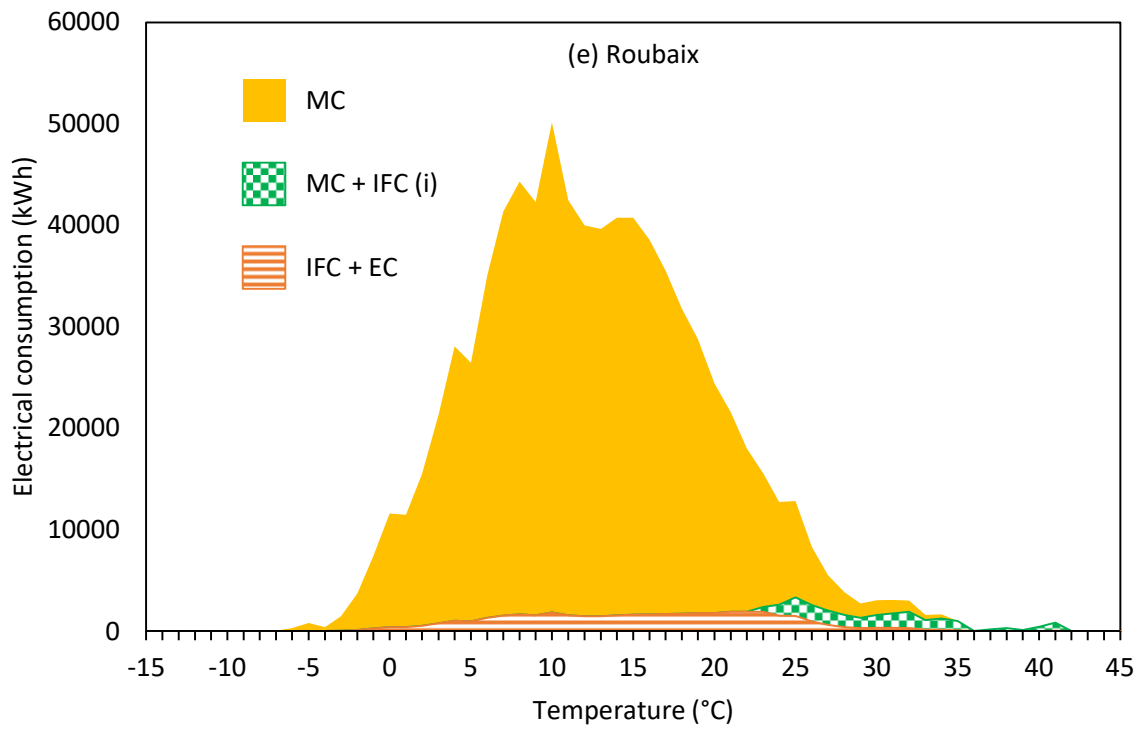
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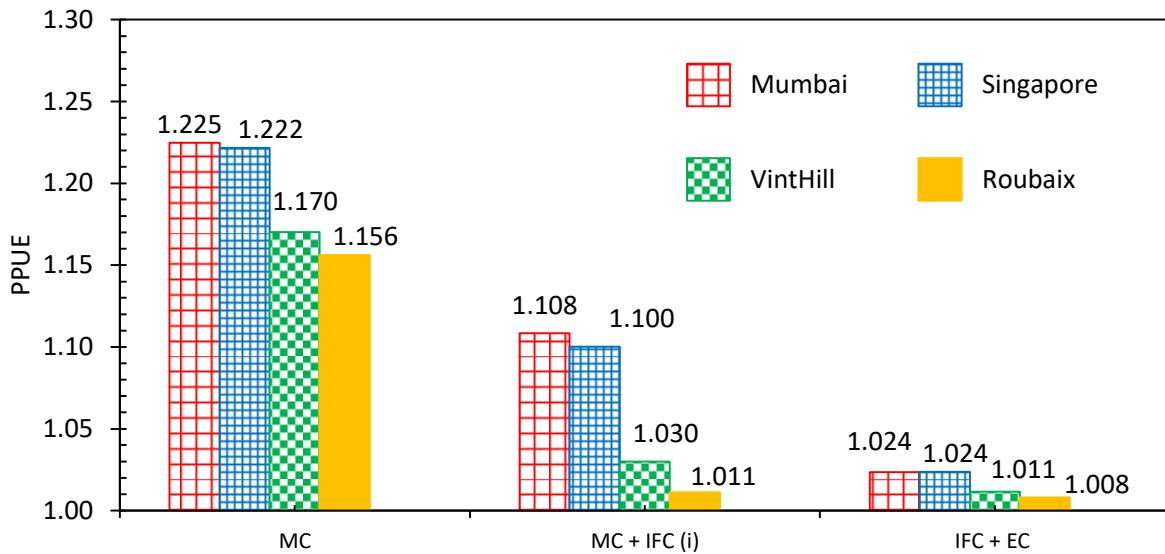
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428

429 Figure 7. (a) Temperature frequency in hours per year for the cities studied; (b), (c), (d), and (e) annual
 430 electricity consumptions of cooling systems of 600 kW DCs under different heat rejection systems in
 431 Mumbai, Singapore, VintHill, and Roubaix, respectively.

432 Figure 8 shows the impact of different cooling systems on the cooling PPUE values at the four locations.
 433 The PPUE decreased by 9.6, 10, 12, and 12.5 % with respect to the MC system for Mumbai, Singapore,
 434 VintHill, and Roubaix, respectively, when the hybrid system was used. Moreover, it decreased by 16.4,
 435 16.2, 13.6, and 12.8 % for Mumbai, Singapore, VintHill, and Roubaix, respectively, when the IFC + EC
 436 system was used.



437
 438 Figure 8. DC cooling PPUE under different cooling heat rejection systems.

439

440 5. Impact of water temperature profile

441

442 5.1 Effect of temperature difference of rack

443 By using the IFC + EC system with a DC temperature difference of 20 K rather than 15 K (Figure 3), the
 444 PPUE values were reduced by approximately 0.3, 0.3, 0.2, and 0.1% and the WUE values by
 445 approximately 42, 38, 49, and 61 % for Mumbai, Singapore, VintHill, and Roubaix, respectively (see
 446 Figure 9(a) and (b)). This is related to the use of the EC system to a lesser extent when the temperature
 447 difference is 20 K because the EC is on when the outdoor temperature is higher than 26 °C (rather than
 448 24 °C) for the case of 15 K.

449 **5.2 Effect of increasing DC water inlet temperature**

450

451 The impact of the increase in the temperature of water supplied to the DC by 5 K on the DC
 452 performance is analysed in this section. This is because it enhances the dry cooler performance and
 453 reduces the DC PPUE and WUE. However, it would increase the ambient air temperature and WB inlet
 454 temperature of the racks, as shown in Table 8.

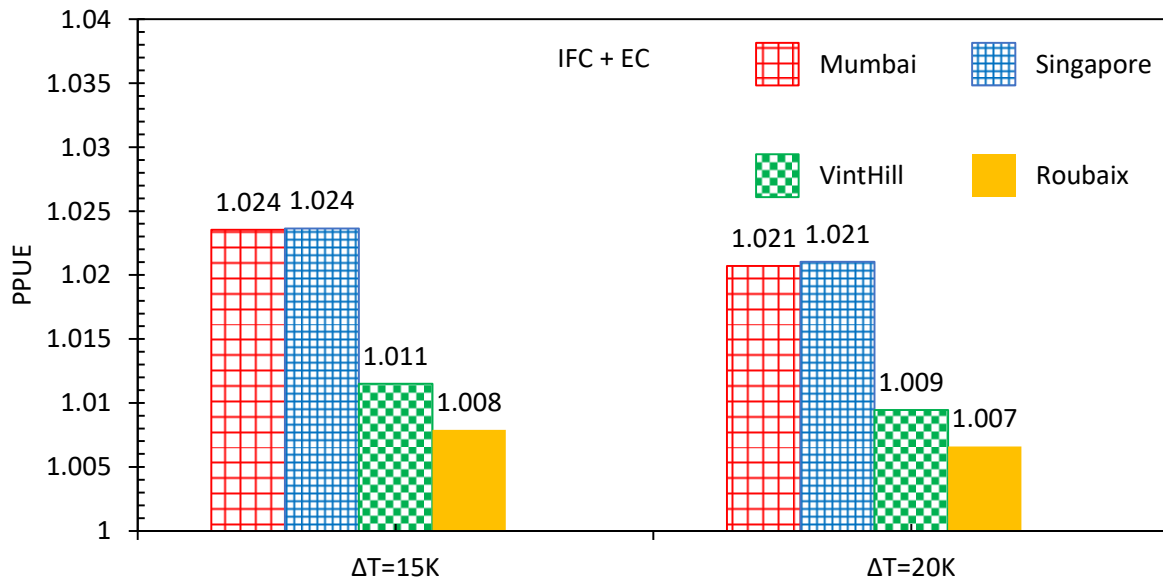
Temperature (°C)	DC Temperature Profile	
	$\Delta T = 20 \text{ K}$	$\Delta T = 20 \text{ K} + 5 \text{ K}$
$T_{\text{Rack-i}}$	27	33
$T_{\text{RDHX_air-o}}$	30	35
$T_{\text{RDHX-o}}$	35	40
$T_{\text{WC-i}}$	45	50
$T_{\text{WC-o}}$	50	55
$T_{\text{Rack-o}}$	47	52

455

456 **Table 8. 20 K + 5 K cooling system topology.**

457 Figure 9(c) and (d) shows the cooling PPUE and WUE, respectively, for the four locations with IFC + EC, a
 458 temperature difference of 20 K, and an increase in the temperature of DC supply-water by 5 K. An
 459 increase in the temperature of supplied water by 5 K resulted in a reduction in PPUE values by 0.4, 0.5,
 460 0.2, and 0.2 % and in WUE values by 38, 37, 30, and 56 % for Mumbai, Singapore, VintHill, and Roubaix,
 461 respectively, compared with the case of 20 K presented in the previous section. An increase in the
 462 temperature of supplied water by 5 K implies a shift in the EC system water supply by 5 K. That is, the EC
 463 system would be activated at 29 °C rather than 26 °C (for the 20 K case). Furthermore, this increment in
 464 water inlet temperature of DC could be handled by all the racks under TC-35 (as described in Section
 465 3.2).

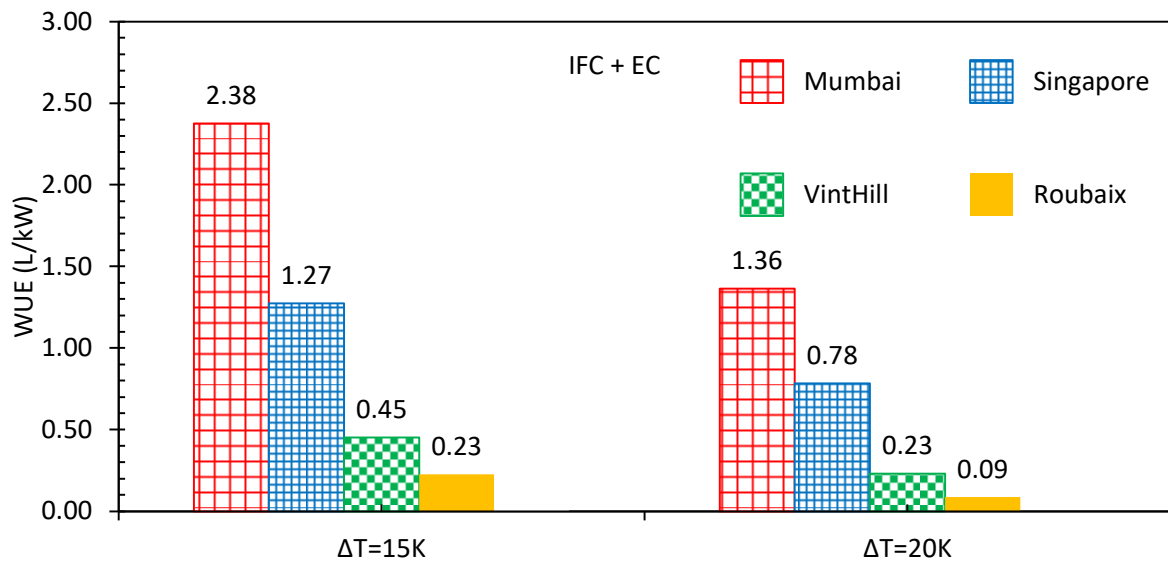
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(a)

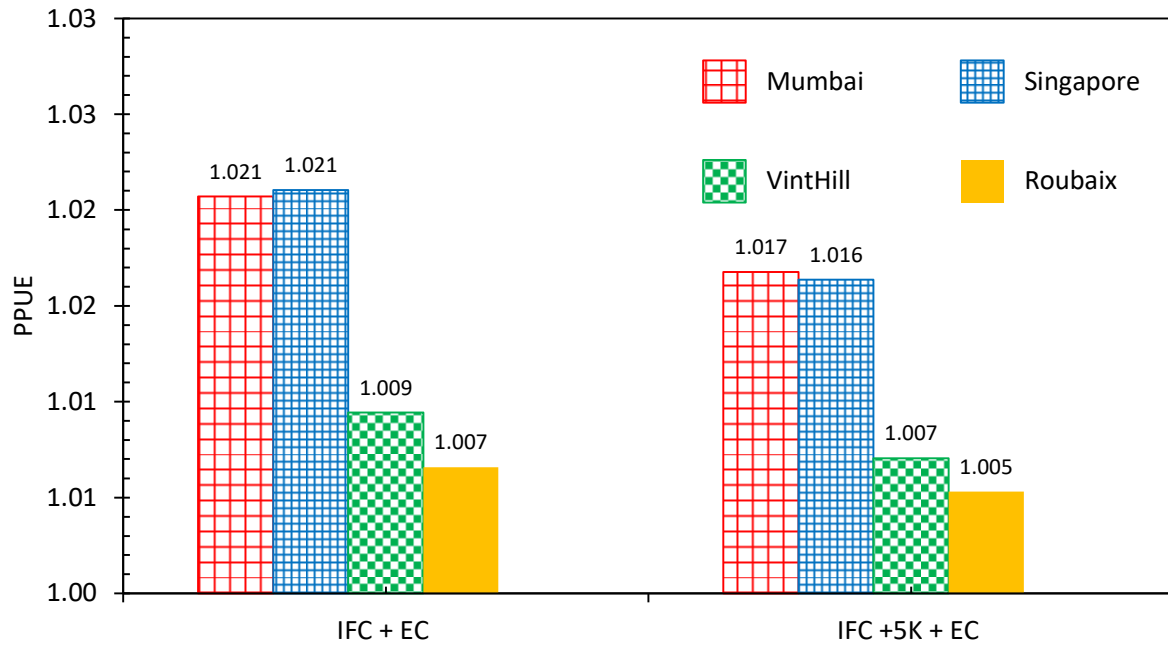


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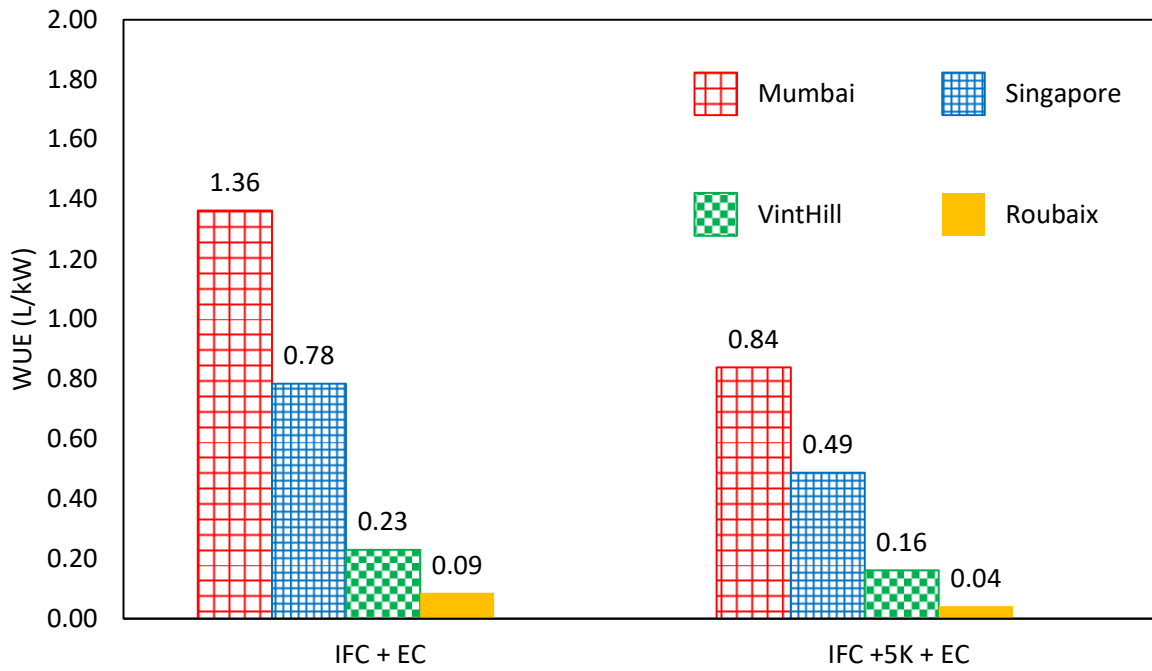
(b)



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(c)



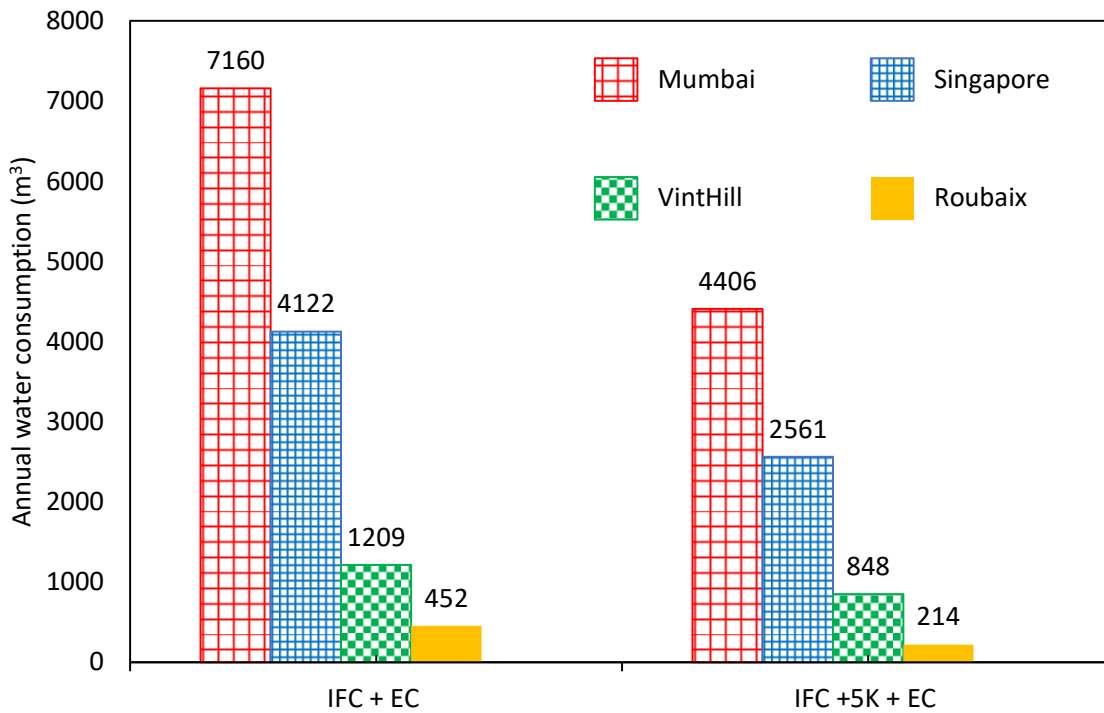
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(d)

476 Figure 9. (a) Cooling PPUE under temperature differences of 15 K and 20 K; (b) WUE under temperature
 477 differences of 15 K and 20 K; (c) Cooling PPUE when the temperature of water supplied to DC increases
 478 by 5 K under 20 K; (d) WUE when the temperature of water supplied to DC increases by 5 K under 20 K.

479 The water consumption of DCs has global and regional impacts on ecosystems (e.g., on river flow and
 480 groundwater levels). This, in turn, may influence the overall water resources of a territory in the context
 481 of water scarcity. Thus, it is vital to reduce the WUE values of DCs, which affect the annual water
 482 consumption of DCs. Figure 10 shows a comparison of the annual water consumption of a 600 kW DC for
 483 different climatic conditions with an increase in the temperature of water supplied to DC by 5 K under a
 484 temperature difference of 20 K. For example, an increase in the supplied-water temperature by 5 K
 485 caused a reduction in the annual water consumption from 7160 m³ to 4406 m³ (62%) for Mumbai city
 486 and from 452 m³ to 214 m³ (47%) for Roubaix.



487
 488 Figure 10. Comparison of annual water consumption by 600 KW DC for different climatic conditions with
 489 an increase in the temperature of water supplied to DC by 5 K under a temperature difference of 20 K.

490 The previous results are summarised in Table 9. It shows the variation in PPUE under different climatic
 491 conditions and for different cooling systems and temperature profiles. The improvements in WUE for
 492 the IFC + EC system are shown in Table 10.

Cases			Sites			
			Mumbai	Singapore	VintHill	Roubaix
			PPUE			
Case 1	MC	-	1.225	1.222	1.170	1.156
Case 2	MC + IFC	-	1.108	1.100	1.030	1.011
Case 3	IFC + EC	dT = 15 K	1.024	1.024	1.011	1.008
Case 4	IFC + EC	dT = 20 K	1.021	1.021	1.009	1.007
Case 5	IFC + EC	dT = 20 K + 5 K	1.017	1.016	1.007	1.006

494 Table 9. PUE values under different climatic conditions and for different cooling systems and
 495 temperature profiles

dT	Sites			
	Mumbai	Singapore	VintHill	Roubaix
	WUE (l/kWh)			
15 K	2.38	1.27	0.45	0.23
20 K	1.36	0.78	0.23	0.09
20 K + 5 K	0.84	0.49	0.16	0.04

496

497 Table 10. WUE values for improvements in IFC + EC system.

498 6. Conclusion

499

500 This paper presents a new cooling topology for information technology racks based on liquid cooling
 501 deployed within OVHcloud data centres. Within this topology, the rack-cooling system is based on a
 502 combination of close-coupled cooling and direct-to-chip cooling. An experimental investigation was
 503 conducted at the rack level to validate the direct impact of temperature difference (15 K and 20 K) on
 504 operational information-technology racks under thermal conditions of 27 and 35 °C. Five racks with
 505 operational servers were tested. A temperature difference was validated for all the IT racks. The 20 K
 506 temperature-difference profile was validated under the two thermal conditions with the proposed rear-
 507 door heat exchanger configuration.

508 The impact of these temperature difference profiles (15 K and 20 K) on the data-centre performance
 509 was analysed using three heat rejection systems (a mechanical cooling system using chillers, indirect
 510 free cooling, and hybrid chillers with integrated intelligent dry coolers) under four climatic conditions for
 511 a data centre of 600 kW. Our results can be summarized as follows:

- 512 • Adding a dry cooler to the chiller (hybrid mode) reduced the average electrical consumption by
 513 at least 52 % compared with the mechanical cooling system in all the four locations (Mumbai,
 514 Singapore, VintHill, and Roubaix).
- 515 • Indirect free cooling equipped with an evaporative cooling system showed optimal energy
 516 savings (a reduction in annual power consumption of at least 89 % compared with the
 517 mechanical cooling system). The cooling partial power usage effectiveness also reduced (by at
 518 least 16 %) compared with that of the mechanical cooling system.

519 The impact of the water temperature profile on the partial power usage effectiveness and water usage
 520 effectiveness of data centre was analysed to optimise the indirect free cooling system equipped with an
 521 evaporative cooling system through two approaches: rack temperature difference and by increasing the
 522 water inlet temperature of the data centre.

- 523 • Increasing the temperature difference of the racks from 15 K to 20 K significantly reduced the
 524 water usage effectiveness and marginally reduced the partial power usage effectiveness (by
 525 approximately 40 % and 0.1 %, respectively).

526 • Increasing the temperature of cold facility water supplied to data centre by 5 K under the 20 K
527 temperature-difference profile significantly reduced the water usage effectiveness and
528 marginally reduced the partial power usage effectiveness (by approximately 38 % and 0.1 %,
529 respectively).

530 With reference to the high return water temperature (which exceeds 50 °C), the application of this
531 liquid-cooled data centre topology enables the use of the waste heat of IT equipment for other
532 applications such as domestic hot water, network heating, and industrial applications.

533 Many investigations could be conducted in future work, such as hybrid liquid cooling by integrating
534 water cooling with a dielectric fluid (which has a higher thermal conductivity than air). In addition, the
535 footprint (kW/m²), capital expenditure, operating expenditure, and energy at the data-centre level can
536 be analysed.

537 Appendix A

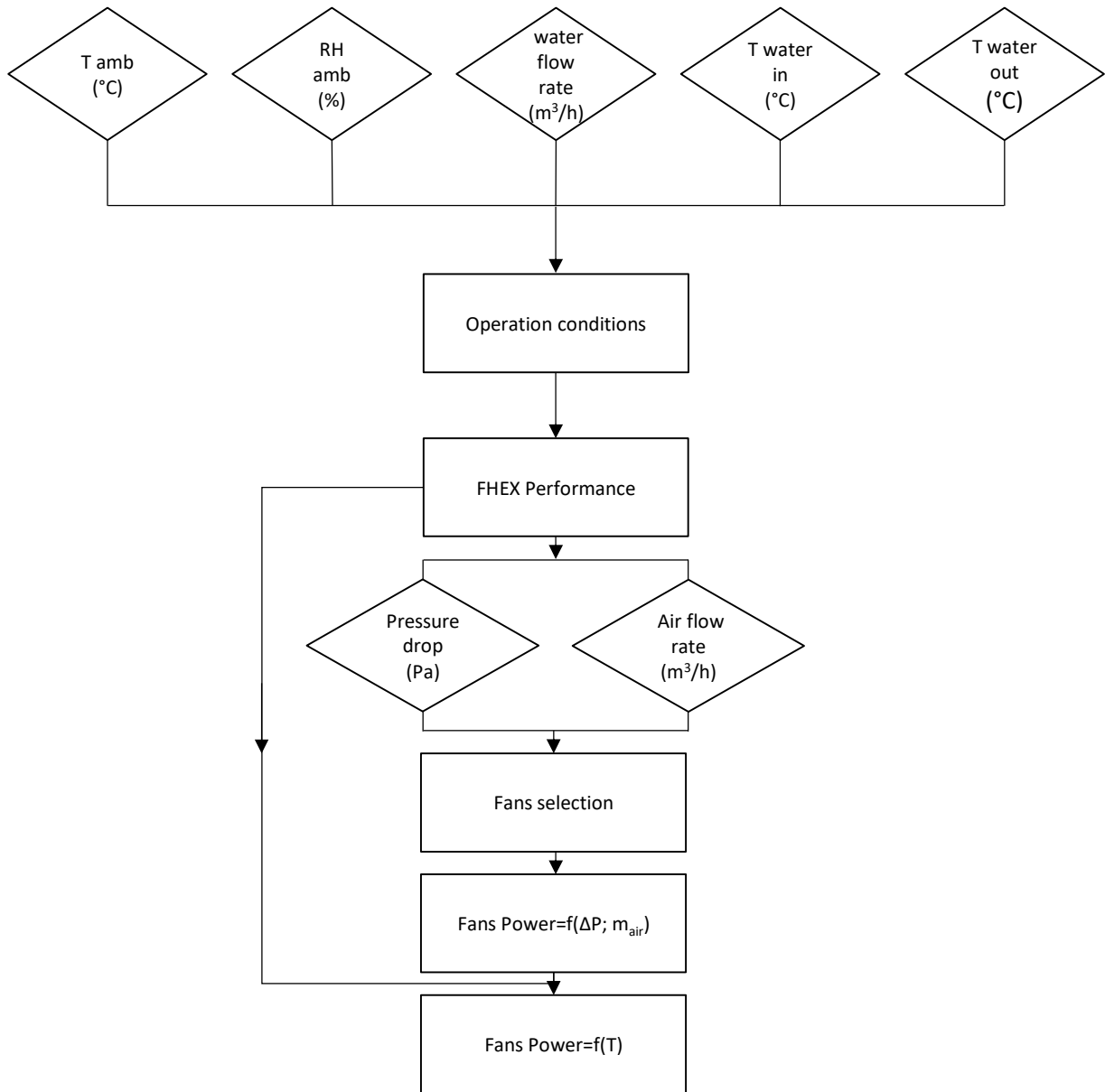
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539 Appendix A provides detailed information on the locations of temperature, pressure, differential
540 pressure, and flow-rate sensor measurement and the names of the sensors for the climatic chamber test
541 bench (see Figure 4). In addition, it provides detailed information on the methodologies for calculating
542 power consumption and WUE (see Figures 10 and 11, respectively).

543

544 Figure 4 (d) shows the climatic chamber test bench. The air temperature sensors, wall temperature
545 sensors, and water temperature sensors are illustrated in green, blue, and orange, respectively. A
546 thermocouple that measures air temperature was installed on each console suction port. Three
547 thermocouples each were installed on the inlet and outlet of each RDHX to measure the hot air and cold
548 air temperatures, respectively. With regard to the air cooling circuit (AC), two immersed thermocouples
549 were installed on the rack's inlet and outlet manifolds to measure the water temperature. A
550 thermocouple was installed at each RDHX outlet to measure the water temperature. A thermocouple
551 was installed at the AC outlet to measure the temperature of the water entering the PHEXs of the CDU.
552 For the water cooling circuit (WC), two thermocouples were installed on the water block inlet and outlet
553 manifolds to measure the water temperature. Two Kobold [37] 5–90 l/min flow-rate sensors were
554 installed in the AC and WC circuits to measure the flow rate of the water fed to the rack and its WBs,
555 respectively. Two 0–6 bar Kobold pressure sensors were installed on the inlet and outlet of the rack. A
556 0–6 bar Kobold pressure sensor was installed at the inlet of the CDU PHEXs (AC circuit) to measure the
557 water pressure after the RDHXs. Two 0-6 bar Kobold pressure sensors were installed on the WC inlet
558 and outlet manifolds. Two Kobold differential pressure sensors (3.73–373 mbar) were installed on the
559 AC circuits to measure the pressure drop of the RDHXs and the total pressure drop of the rack.
560 Moreover, a Kobold differential pressure sensor was installed on the WC circuits to measure the overall
561 pressure drop of the CDUs.

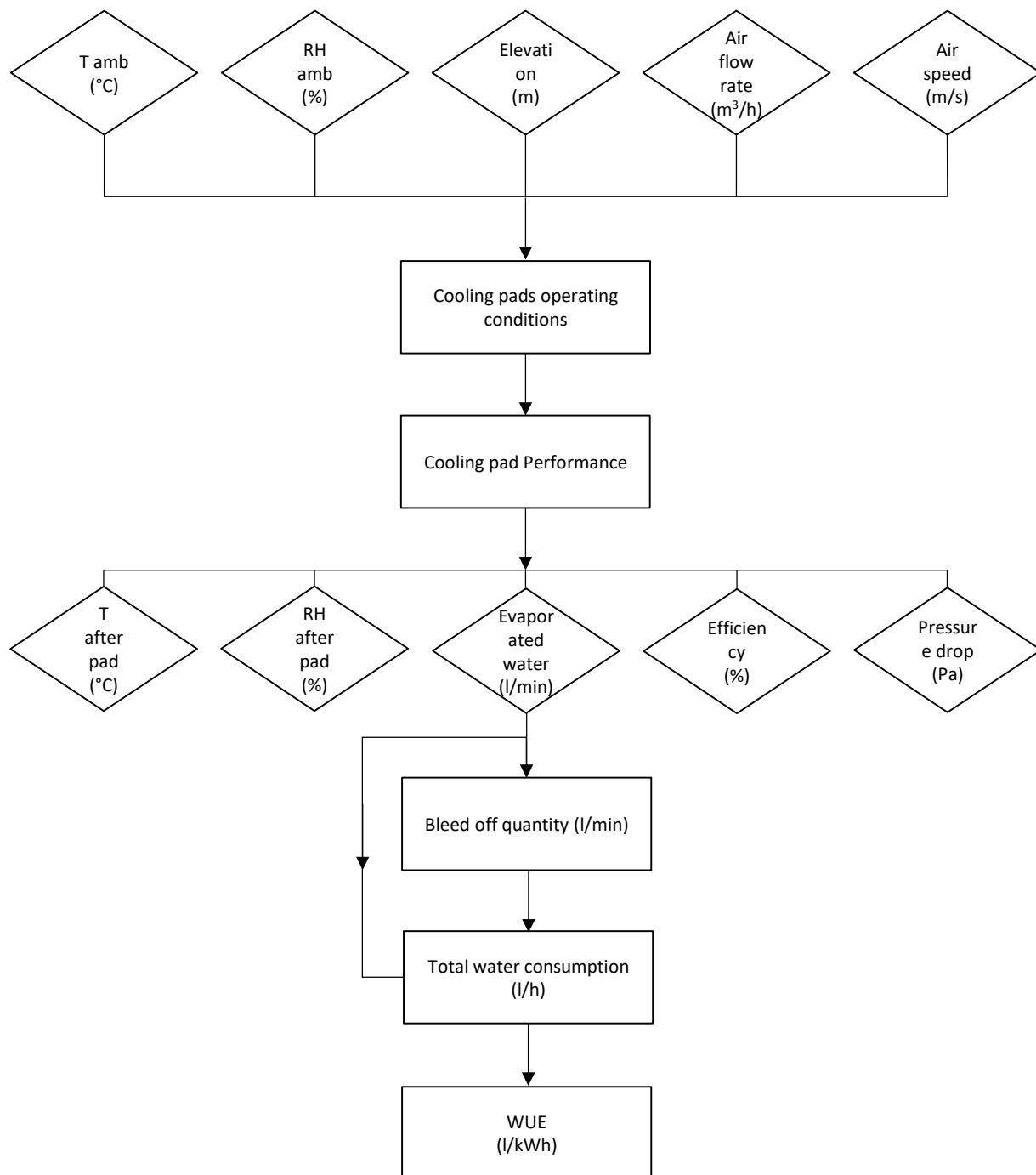
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563

564

Figure 11. Methodology for calculating power consumption.



565

566

567

568

569

Acknowledgement

Figure 12. Methodology for calculating WUE.

570 The authors of this article wish to thank the OVHcloud R&D-Cooling team for their help during concept
 571 development, test bench design, and the test.

572 **Nomenclature**

573

General Nomenclature		Greek symbols and subscripts	
<i>AC</i>	Air Cooling	Δ	Increment, deviation
<i>WUE</i>	Water Usage Effectiveness	Σ	Sum
<i>CDU</i>	Cooling Distribution Unit	η	Efficiency
<i>PSS</i>	Pumping Substation	<i>A</i>	Constant
<i>DC</i>	Data Centre	<i>B</i>	Constant
<i>DSI</i>	Direct Steam Injection	<i>C</i>	Constant
<i>FHEX</i>	Finned Heat Exchanger	<i>I</i>	Inlet, index
<i>IFC</i>	Indirect Free Cooling	<i>M</i>	Constant
<i>IT</i>	Information Technology	<i>N</i>	Constant
\dot{m}	Mass flow rate (kg/s)	<i>O</i>	Outlet, constant
<i>MC</i>	Mechanical Cooling	<i>P</i>	Constant
<i>P</i>	Electric power (W), Pressure (Pa)	<i>X</i>	Constant
<i>PHEX</i>	Plate Heat Exchanger	<i>Y</i>	Constant
<i>PUE</i>	Power Usage Effectiveness	<i>Z</i>	Constant
<i>PPUE</i>	Partial Power Usage Effectiveness		
<i>Q</i>	Heat load (W)		
<i>EC</i>	Evaporative Cooling		
<i>RDHX</i>	Rear-Door Heat Exchanger		
<i>T</i>	Temperature (°C)		
TC	Thermal Conditions		
<i>WB</i>	Water Block		
<i>WC</i>	Water Cooling		

574 **7. References**

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Performance analysis of new liquid cooling topology and its impact on data centres

