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Experimental investigation of an optimized indirect free cooling system including a dry cooler equipped with evaporative cooling pads for data center☆

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ABSTRACT

Different heat rejection systems could be used to discharge the heat of liquid cooled data center to the ambience. The dry cooler as an indirect free cooling solution is one of the most used, where outside air is applied as a cooling fluid for its finned heat exchangers (FHEXs). In ambiences where dry coolers ambient temperatures are higher than supplied FHEX's water temperature, evaporative cooling system can be used as pre-coolers. This paper presents an experimental investigation conducted on an indirect free cooling system including a dry cooler equipped with evaporative cooling pads (IFC+EC) under 20 K data center temperature difference for high outdoor conditions, variable fan speed, reduction in cooling pad's surface and increasing in water supply temperature. The results show that the dry cooler is successfully operated under 20 K temperature difference. Furthermore, by increasing the air speed from 2 m/s to 3 m/s, the pads' outlet air temperature increases by 0.6 K, the relative humidity tends to decrease about 9% and its efficiency decreases from 97% to 88%. Surface clogging had no significant impacts. A slight rise of 1.24 K in air outlet temperature and a decrease of about 3.3% and 2.5% in relative humidity and cooling pad thermal efficiency respectively were detected while increasing water supply temperature from 23 °C to 44 °C. This allowed authors to propose an optimized IFC+EC system with precooling DC supply water before the dry cooler to reduce its cooling demand by at least 31%.

1. Introduction

Cooling systems within data centers (DCs) constitute the most substantial share of overall electrical consumption, second only to IT equipment. Consequently, it is imperative to tackle environmental concerns by ensuring the deployment of energy-efficient cooling systems for DCs. The workload of heat rejection systems, employed to expel the heat generated in data centers (DC) to the external environment, can be markedly diminished through the judicious utilization of locally available free cooling methods (Malone and Belady, 2008; Udagawa et al., 2010; Lee and Chen, 2013; Zhang et al., 2017; Malkamäki and Ovaska, 2012). In particular, data centers (DCs) employing liquid cooling present a greater potential to dissipate heat into the atmosphere using a dry cooler. This effectively eliminates the need for a cooling tower or chiller plant in a majority of climate (Lee and Chen, 2013).

In ambiences where dry coolers ambient temperatures are higher than liquid cooling supplied temperature, evaporative cooling (EC) can be used as pre-coolers (Shao et al., 2019). Prior to the fans pulling ambient air through finned heat exchangers, the air undergoes adiabatic pre-cooling as it passes through a humidification media. This process involves water evaporation in the incoming air, thereby enhancing the cooling capacity.

In recent years, climate change has increased the magnitude and period of dry and wet seasons globally (Hansen et al., 2015; Chou et al., 2013). Hansen et al. (2010). demonstrated that the global temperature in 2015 was + 1.13 K relative to the 1880–1920 mean. Erik et al. (2018). elucidated that Europe is projected to experience warming across all seasons in the future, and these temperature increases exhibit a high level of consistency and robustness across the ensemble, despite substantial natural variability in the climate. Additionally, the simulated temperature changes in Europe generally surpass the global mean warming.

Different evaporative cooling system can be employed to cool inlet

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Nomenclature

Keywords	Greek Symbols
AC	Air Cooling
WUE	Water Usage Effectiveness
PSS	Pumping SubStation
DC	Data Center
DSI	Direct Steam Injection
FHEX	Finned Heat EXchanger
IFC	Indirect Free Cooling
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (Pa)
PHEX	Plate Heat EXchanger
Q	Heat load (W)
EC	Evaporative Cooling
RH	Relative Humidity (%)
T	Temperature (°C)
Δ	Increment
Σ	Sum
a	Constant
b	Constant
c	Constant
i	Inlet, index
η	Efficiency

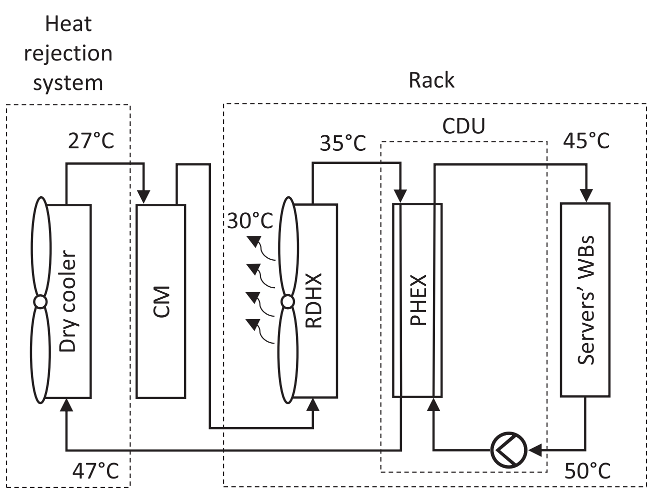


Fig. 1. Indirect Free Cooling (IFC) system architecture in a liquid cooled DC.

air (ASHRAE, 2016). Among them is the direct steam injection system (DSI). The process of humidification within a DSI can be simplified by adding liquid and vapor steam directly into air. DSI systems suffer from many problems, some of which are related to human health and the environment, and others in terms of effectiveness and cost. Among them:

- Development of bacteria, where droplet sizes between 1 and 5 μm carry Legionella bacteria far enough into the human body (Nocker et al., 2020). Portier et al. (2016). explained that Legionella can in some instances reach high concentrations due to beneficial conditions found in cooling water including warm temperatures, nutrients, iron and biofilms. Ishimatsu et al (Ishimatsu, et al.,null). demonstrated that air around a cooling tower is contaminated with L. pneumophila (1.2 ± 0.3 ×105 CFU/100 ml).
- Complex and expensive of high pressure pumping system
- Erosion is caused by continued high-pressure liquid flowing through the spray nozzle orifice over time. This flow gradually removes metal and causes the orifice to enlarge. As a result, flow increases, pressure decreases, and the spray pattern becomes irregular.
- Excessive use of water and the impossibility of recovery

2. Background of the research

Dry coolers, also known as dry cooling towers, play a pivotal role in the cooling systems of data centers (DCs). In Fig. 1, an architecture of an Indirect Free Cooling (IFC) system is depicted within a liquid-cooled DC. External air is utilized to cool the liquid circulated among various cooling components installed in the DC, eliminating the need for a refrigeration process. The Rear Door Heat Exchanger (RDHX) combines fans and a finned heat exchanger positioned on the rear side of the racks. All IT equipment, excluding CPUs and GPUs, undergo cooling through the RDHX. CPUs and GPUs are subject to liquid cooling through direct-to-chip cold plates utilizing water as a coolant. The Coolant Distribution Unit (CDU) consists of a pump and a plate heat exchanger (PHEX). Facility water enters the rack and passes through three rear-door heat exchangers, effectively cooling hot air. Subsequently, the water flows through the CDUs within the rack.

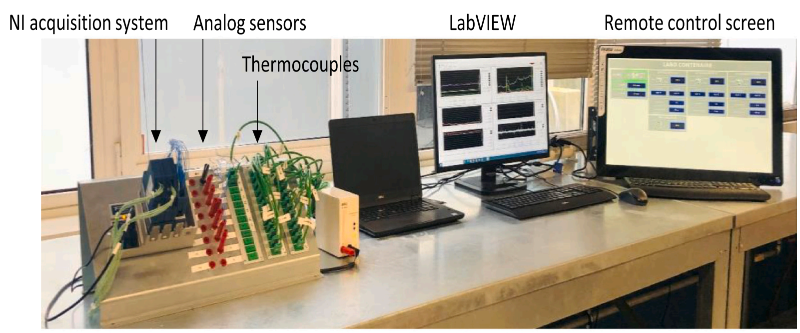
Research efforts have increased lately to design low-cost and environmentally friendly technologies to better condition the indoor temperature of human, plant, animal and DC facilities. Although there are many methods available, the evaporative pad cooling techniques have continuously been demonstrated as effective (Chen et al., 2011; Liao et al., 1998; Ashok Warke and Jaiwantrao Deshmukh, 2017). Liao et al (Liao et al., 1998). explained that cooling pads technology remains as one of the least expensive techniques to bring dry-bulb temperature to a more comfortable range. Warke et Deshmukh (Ashok Warke and Jaiwantrao Deshmukh, 2017) demonstrated that, compared to the local materials, the effectiveness of the pads in decreasing order of magnitude is: Cellulose > Aspen > Khus pads.

Evaporative cooling pads are commonly employed to serve dual functions of winter humidification and summer cooling. These pads utilize a porous core, initiating the evaporation process when air, entering at a specific velocity, comes into contact with water circulated over the media. This method operates on an adiabatic principle, simultaneously humidifying and cooling the air. The rate of evaporation is contingent on factors such as air temperature, flow rate, and, notably, humidity (Ashok Warke and Jaiwantrao Deshmukh, 2017; Koca et al., 1991; Franco et al., 2014). Principally, the amount of heat that can be rejected from the water to the air is directly tied to air relative humidity. Air with a lower relative humidity ratio has a greater ability to absorb water through evaporation due to low quantity of water already contained. Besides, Warke et Deshmukh (Ashok Warke and Jaiwantrao Deshmukh, 2017) indicated that when air speed decreases and pad thickness increases, the optimum point may occur. Franco et al. (2014). manifested that regarding the cellulose pads, as the water flow increases the volume of water circulating over the pad increases and therefore the porosity and volume of air that can pass through the pad decrease.

Conversely, it is essential to exercise caution when handling cooling pads. The pads possess inherent filtration and scrubbing properties due to the water-washing effect within the filter-like channels. Consequently, only pure water undergoes evaporation. Therefore, it is imperative to flush contaminants, gathered from both the air and water, from the system. To mitigate the accumulation of contaminants in the pan and on the media, a continuous bleed or regular pan flushing is advised.

This work focuses on an experimental study to develop and validate the impact of evaporative cooling pads on DCs dry coolers system. Tests are conducted to highlight the evaporation process, cooling pads and dry cooler efficiency under four cases: high outdoor conditions, air speed

(a)



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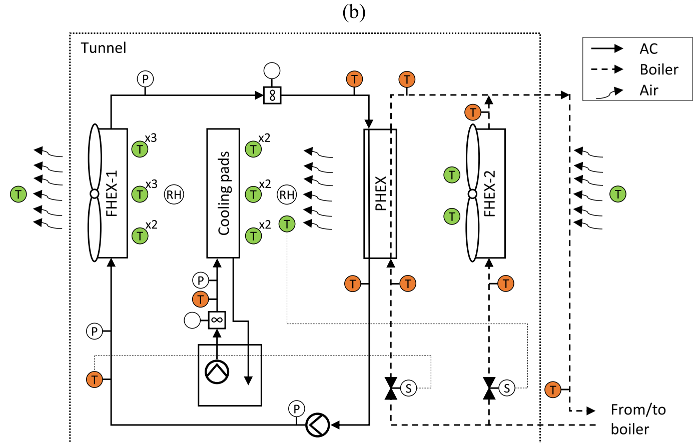
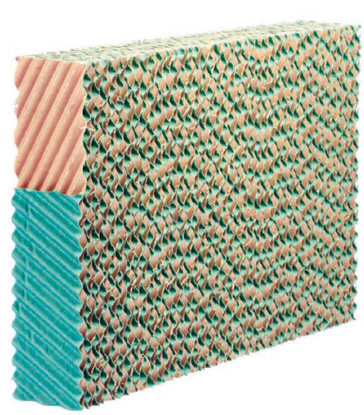


(c)



(d)

Fig. 2. (a) Dry cooler test tunnel; (b) Dry cooler experimental setup control room; (c) Schematic representation of the experimental setup; (d) Munters Celdek 7060–15 cooling pads.

variation, cooling pad's surface clogging and cooling pad's water supply temperature variation. Finally, an optimized indirect free cooling system equipped with evaporative cooling pads was proposed where a pre-cooling process for DC supply water was used before the dry cooler.

3. Cooling infrastructure investigation

3.1. Experimental setup

A dry cooler tunnel is designed and built within OVHcloud laboratories in Croix-France to experimentally validate the transition from 15 K to 20 K water temperature difference on dry coolers. Fig. 2(a) and (b) shows a photo of the test tunnel and its control room respectively.

The experimental setup scheme presented in Fig. 2(c) is composed of a tunnel made of a 40 ft maritime container, cooling circuit, heating circuit and a PSS. The cooling circuit contains a dry cooler to simulate DC cooling. It is composed of one finned heat exchanger (FHEX-1) and 2 fans. EC is assured via Munters Celdek 7060–15 cooling pads, corrugated sheets consisted of impregnated cellulose paper, assembled at different angles (45° and 15°) as shown in Fig. 2(d). 3.75 pads (pad dimension: 1800×600×200mm) are installed vertically in the dry cooler suction port. The media is continually supplied with water via a submersible pump installed in a recovery reservoir. It is assumed that air velocity and water mass flow rate are uniform over the cooling pad air inlet surface. Since water is recirculated constantly through the pads, it reaches a thermal equilibrium with flowing air. Therefore, wetted surface temperature can be considered equal to air input wet-bulb temperature.

The heating circuit is composed of two different apparatuses simulating DC generated heat (DC simulator) and DC outside temperature (ambience simulator):

- DC simulator is composed of a PHEX connected to a boiler via a controlled solenoid valve (Siemens VVF 32.5–40). It is also linked to the dry cooler via a PSS simulating a DC PSS. The substation is composed of 1 operation pump and 1 backup pump. Moreover, all pipes are thermally insulated.
- DC outside conditions are simulated via ambience simulator apparatus installed on the tunnel's inlet. It is composed of a finned heat exchanger (FHEX-2) and 2 axial HyBlade ebm-papst fans (maximum electrical power of 2880 W; maximum rotation speed of 1000 rpm). FHEX-2 is connected to a boiler via a controlled solenoid valve (Siemens VVF 32.5–40) regulating dry cooler inlet air temperature.

Fig. 2(c) also shows the distribution of sensors on the system. A Grundfos 20–400 l/min flow rate sensor is installed in DC circuit to measure water flow rate feeding the dry cooler. All thermocouple which measuring air temperature are illustrated in green color while water temperature sensors are illustrates in orange as shown in Fig. 2(c): two thermocouples are installed for the measurement of water temperature at the inlet and outlet of the dry cooler. Accordingly, the heat load is estimated as follows:

$$Q = \dot{m} \quad Cp\Delta T \tag{1}$$

where $\dot{m}$ (kg/s) is the water flow rate feeding the dry cooler, Cp (kJ/kg/°C) is the specific heat of water, and ΔT (°C) is the water temperature difference in the circuit.

Four thermocouples are installed on the PHEX, one per connection. Two 0–6 bars Kobold pressure sensors are installed on FHEX-1 inlet and outlet, and two other pressure sensors are installed on each pump's outlet. Six temperature sensors and a Kobold capacitive metrology humidity sensor are installed on the cooling pad inlet. Likely, eight temperature sensors and a Kobold capacitive metrology humidity sensor are installed on the cooling pad outlet. The temperature sensors are distributed over the pad in a way creating a measuring mesh. A Kobold 5–90 l/min flow rate sensor, temperature sensor and Kobold pressure sensor are installed on the cooling pad collector to measure water flow rate, temperature and pressure respectively.

Table 1
Uncertainties for different parameters involved in the experimental tests.

Parameter	Uncertainty
Temperature, T (°C)	±0.210 °C
Pressure, P (Pa)	±0.5%
Flow rate, $\dot{m}$ (l/min)	±4 ml/min
Relative humidity, RH (%)	±2%
Heat load, Q (W)	±1.5%
Locations and distances (m)	±1%
Response time (s)	±5%

Table 2
Test cases studied.

	Dry cooler		Cooling pad	
Test cases	Air inlet temperature/ RH (°C) / (%)	Fan's rotation speed (%)	Surface area (m2)	Supplied water temperature (°C)
Case 1: Dry cooler performance	38.3 → 42.1/ 20→17	100	4.05	20
Case 2: Impact of Fan's speed	39 / 20	50 → 100	4.05	20
Case 3: Impact of clogging effect	39 / 20	100	3.95	20
Case 4: Impact of pad's supplied water	39 / 20	100	4.05	20 → 44

Two temperature sensors are installed on the DC ambience simulator to measure heated air temperature, 30 cm far from FHEX-2 outlet. Besides, two temperature sensors are installed on FHEX-2 inlet and outlet collectors. Two temperature sensors are installed outside the tunnel for measuring ambience temperature. Uncertainties are evaluated using the method of Kline and McClintock (1953). For example, the uncertainty of the thermal heat load (Q) is evaluated by:

$$\frac{\partial Q}{Q} = \left[\left(\frac{\partial Q}{\partial \dot{m}} xa \right)^2 + \left(\frac{\partial Q}{\partial T_1} xb \right)^2 + \left(\frac{\partial Q}{\partial T_2} xc \right)^2 \right]^{1/2} \tag{2}$$

where $\dot{m}$ is the water flow rate, T_1 inlet temperature, T_2 outlet temperature while a, b and c signify the uncertainty of $\dot{m}$, T_1 and T_2, respectively.

Table 1 shows the uncertainties for different parameters involved in the measurements.

All temperature sensors are type K thermocouples with an accuracy of ±0.210 °C after calibration process. National instruments data acquisition system NI cDAQ-9174, a compact DAQ system, is used to record all temperatures, pressures and flow rates throughout each experimental test as shown in Fig. 2(b). Then the data are read, processed, and stored using a program running in LabView with a frequency of one measure per second (National Instruments, Online). Besides, the solenoid valve is controlled remotely by a Carel controller.

Before starting the tests, the experimental loop is fully filled with water and then air is vented from high points, making sure that the whole circuit is free of air. The dry cooler circuit flow rate is manually adjusted depending on required heat load and temperature difference of 20 K. Cooling pads flow rate is adjusted depending on manufacturer recommendation and external conditions. Fans and solenoid valves are controlled to assure that required boundary conditions are well attained.

4 tests are conducted to validate the dry cooler operation with

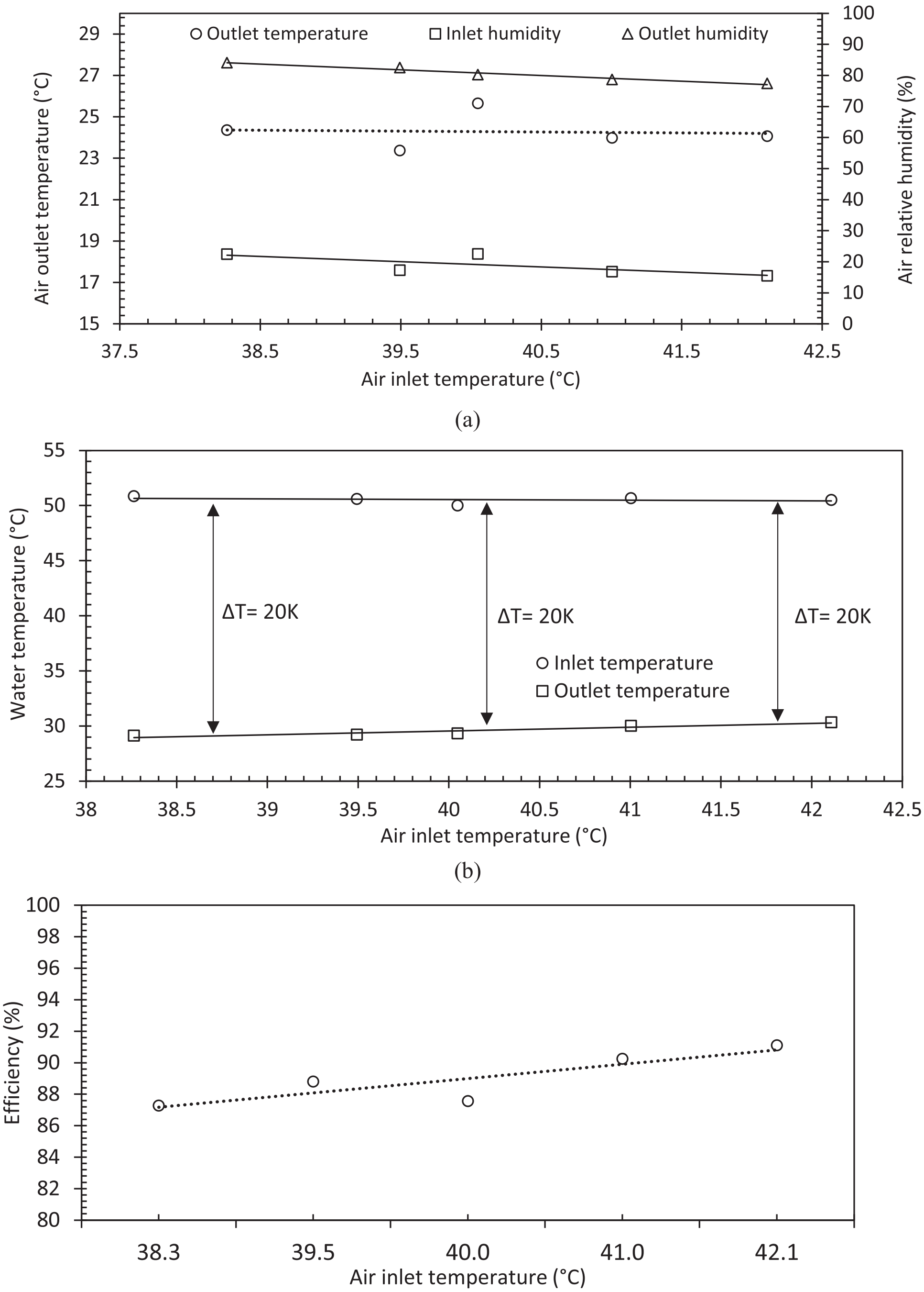


Fig. 3. Impact of outdoor temperature and relative humidity on cooling pad outlet air (a); on dry cooler performance (b); cooling pad thermal efficiency (c).

cooling pad EC system under 20 K temperature difference for high outdoor conditions (1), different fan speed (2), simulating reduction of cooling pad's area (3) and increasing pad water supply temperature (4). These tests are synthetized in Table 2. This allowed authors to propose an optimized IFC+EC system with precooling DC supply water before the dry cooler reducing cooling demand.

For each test, dry cooler's water outlet temperature, cooling pad's outlet air temperature and relative humidity are measured and its thermal efficiency is computed. The latter is defined as:

$$\eta = 100 \times \frac{T_{dair-_i} - T_{dair-_o}}{T_{dair-_i} - T_{wair-_i}} \quad (3)$$

where T_{dair-_i} is inlet air dry bulb temperature, T_{dair-_o} is outlet air dry bulb temperature and T_{wair-_i} is inlet air wet bulb temperature.

4. Results

Evaporation method using cooling pads is considered as a pre-cooling process making outside air an efficient coolant for dry coolers in critical conditions, where air intake temperature would range from 38 °C to 42 °C at relative humidity ratios less than 20%. This range is determined based on statistics collected from several OVHcloud's DCs located in Northern Europe (France, England, Germany and Poland), USA (VintHill and Hillsborough) and Canada (Beauharnois). FHEX-1 is supplied with a water flow rate of 6.5 m^3 /h and air velocity of 3 m/s. DC ambient air temperature is varied from 38.3 °C to 42.1 °C. Fig. 3

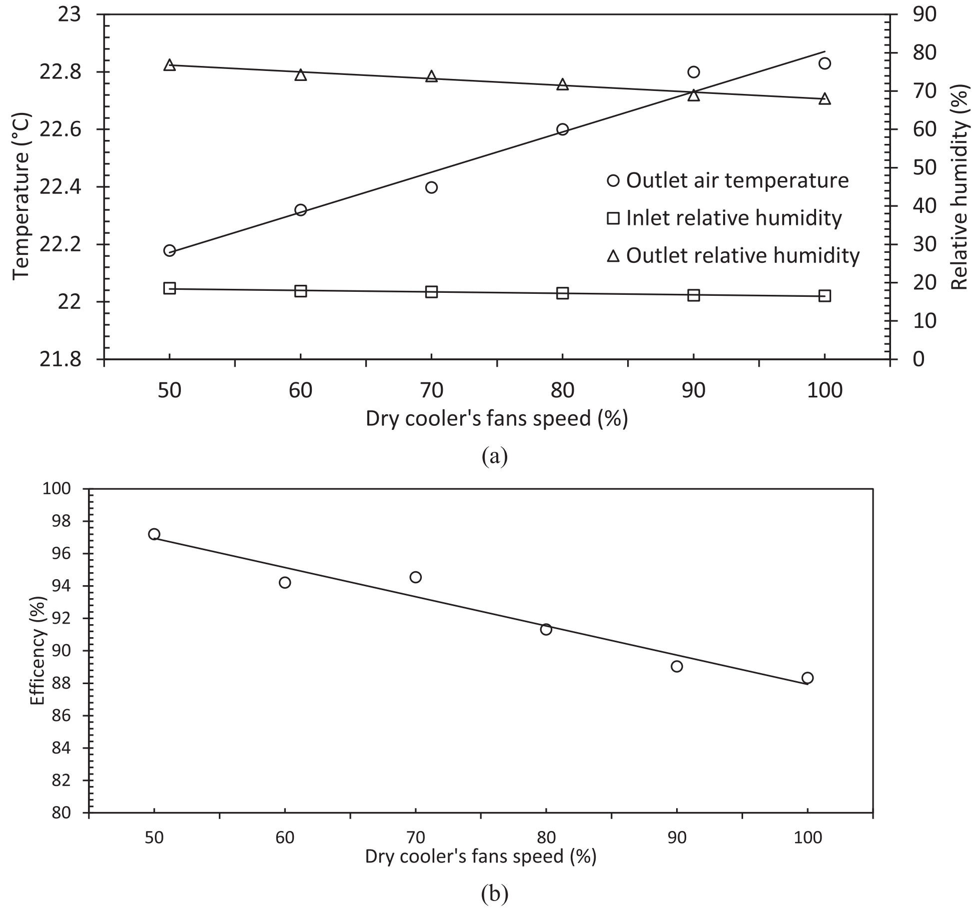


Fig. 4. Cooling pads outlet conditions (a); thermal efficiency (b) under fan speed variation.

shows the impact of DC outside air temperature on the dry cooler's performance and cooling pads efficiency. The impact of the cooling pads on dry cooler air and water temperature are presented in Fig. 3(a) and Fig. 3(b) respectively, while the cooling pad efficiency is presented in Fig. 3(c). Dry cooler's water return temperature stabilized on 30 °C with a temperature difference of 20 K even with outside temperature reaching 42.1 °C. Air relative humidity globally increased from 20% to 80% while air temperature at the pad's outlet maintained between 24 and 25 °C. Besides, cooling pad shows a stable thermal efficiency between 88% and 90%.

Fig. 4(a) shows the impact of fans rotation speed (air flow rate entering the pads) on the pads air outlet temperature and relative humidity. Fig. 4(b) shows the pads' efficiency relative to fans rotation speed. Pads' inlet air temperature and humidity are fixed to 39 °C and 20% respectively. Fans rotation speed is varied from 50% RPM to 100% RPM (with a 10% step) corresponding to an air velocity of 2–3 m/s on the pads respectively. The water flow rate supplied to the pads is determined based on the technical data provided by the manufacturer. It is shown that pads' outlet temperature increases with the increase of fans rotation speed. The total growth is of 0.6 K whereas the relative humidity tends to decrease about 9%. Moreover, the efficiency is higher at low speeds due to the better contact of air with pads' water, providing the evaporation process sufficient time to saturate air. At fan speed 50% RPM, cooling pad's efficiency is 97% while by increasing the fans speed to 100% it will be decrease to 88%.

Several external factors may impede the operation of EC using cellulose pads. That is, dirt or leaves could be sucked by the dry cooler's fans reducing the suction surface area. To simulate the impact of such conditions, especially leaves, a test simulating the suction of 20 leaves is conducted. 20 plastic sheets of 10 × 5 cm each were attached to the pads' inlet port clogging a cooling pad surface of 1000 cm2. Fig. 5(a) and (b) show the clogging impact on cooling pads air outlet and on dry cooler water outlet temperature. As outdoor air temperature varies from 38.5 °C to 42.2 °C, cooling pad's outlet relative humidity decreases about 5%, while dry cooler's water return temperature increases about 1 K and cooling pad's thermal efficiency decreases 6% with respect to the results of first case study (without any clogging of pad's surface).

Water temperature inside the pads is equivalent to that of DC outside air. Liao et al. (1998). demonstrated that EC water attends a thermal equilibrium with flowing air when it is continually recirculated on the pads. Fig. 6 shows modifications conducted on the test apparatus to highlight the impact of EC supplied water temperature on the cooling performance. A PHEX connected to the boiler is placed on the pads' water supply circuit to variate EC water pumped temperature.

Fig. 7(a) and (b) shows cooling pads' supplied water temperature impact on pads' air outlet condition and its thermal efficiency respectively. Pads' air inlet temperature is of 39 °C and relative humidity is of 20%. Water temperature supplied to the pads is varied from 23 °C to 44 °C. A slight rise of 1.24 K in air outlet temperature and a decrease of about 3.3% and 2.5% in relative humidity and cooling pad thermal efficiency respectively were observed as the water temperature increased up to 44 °C.

A new architecture is proposed for optimized IFC+EC solution as shown in Fig. 8. A PHEX is to link the cooling pads and the dry cooler supply circuits. That is, the facility hot water returning from the DC is to be precooled via the EC pads' supply relatively cold water. As demonstrated before, EC water attends a thermal equilibrium with flowing air when it is continually recirculated on the pads. Accordingly, the heated EC water exiting the PHEX will precool DC outside air without a vital impact of its temperature on evaporation process. Later, EC water will be

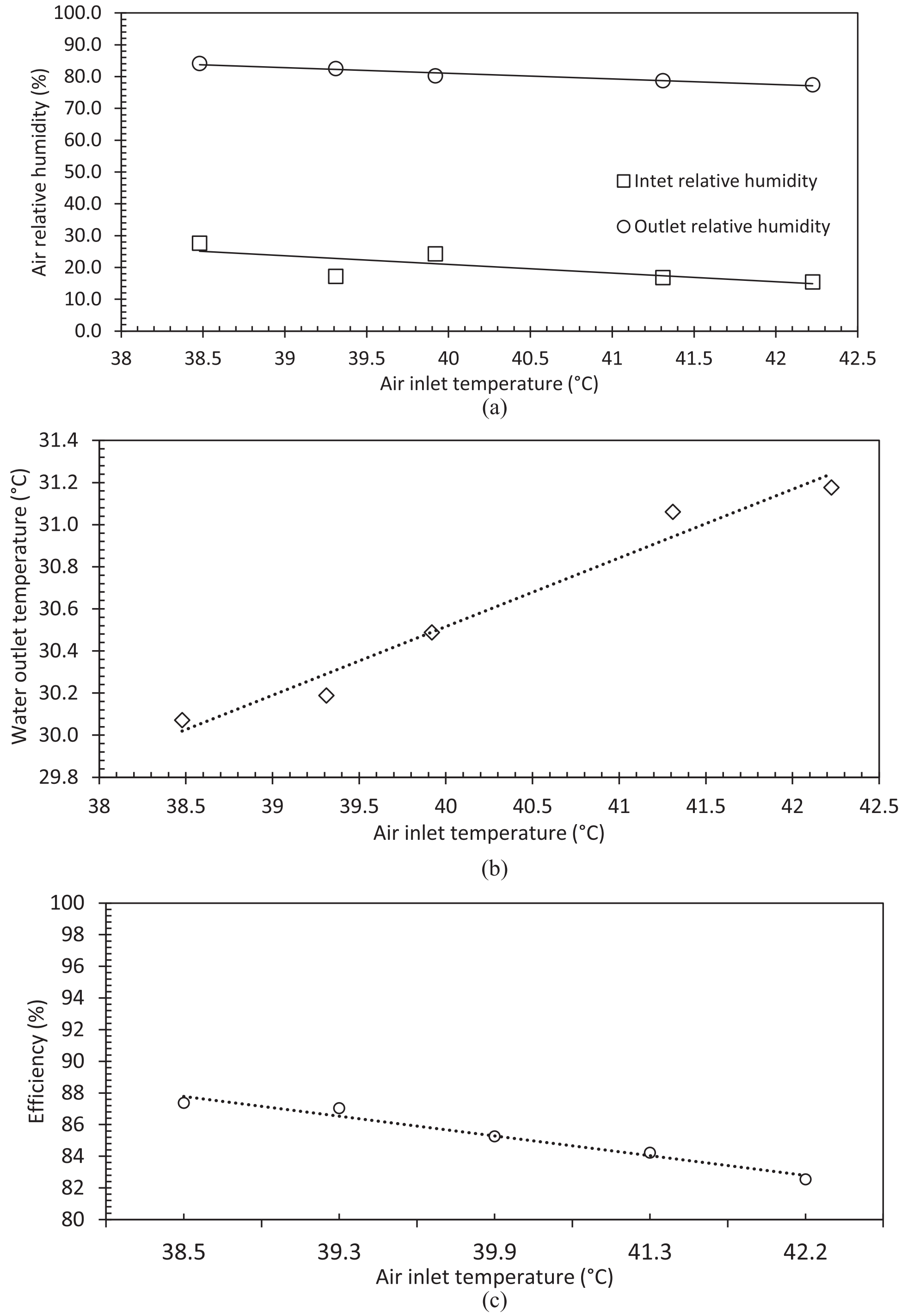


Fig. 5. Impact of leaves sucked by the dry cooler's fans on cooling pad's outlet relative humidity (a); dry cooler water outlet temperature (b); cooling pad's thermal efficiency.

cooled again via the flowing air. The pads' unevaporated water will return to the reservoir with initial air/water equilibrium temperature.

Table 3 shows a case study using the original architecture and optimized IFC+EC architecture. Pads' air inlet temperature is of 42 °C and relative humidity is of 20%. Dry cooler FHEX is supplied with a water flow rate of 6.5 m^3 /h. Dry cooler's return temperature is stabilized on 30 °C via both architectures with a temperature difference of 20 K assuring a heat load of 150 kW. Precooling of AC circuit using EC circuit has a significant impact on the dry cooler's performance. Required dry cooler air flow rate is reduced by 11.4% while pressure drop is reduced by 25%. Dry cooler's power consumption is enhanced by 31%.

5. Discussion and conclusion

In this work, the impact of evaporative cooling pads on dry coolers performance was investigated experimentally as a function of DC temperature difference for different high outdoor conditions, fan speed and cooling pad's surface area, as well as for different pad's water supply temperature.

On DC level, the dry coolers equipped with evaporative cooling pads successfully operated under 20 K temperature difference even under

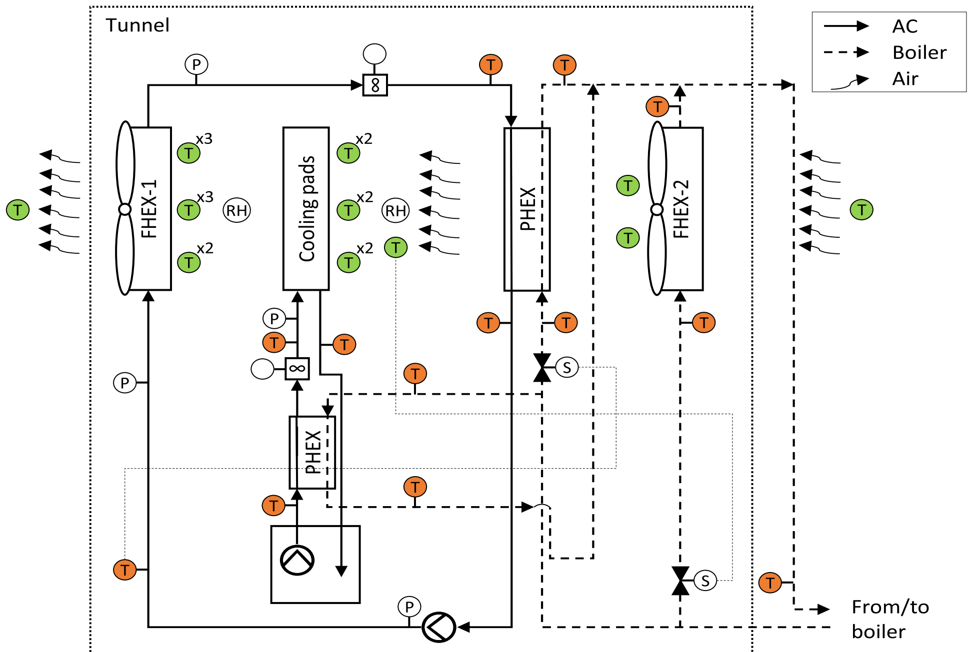
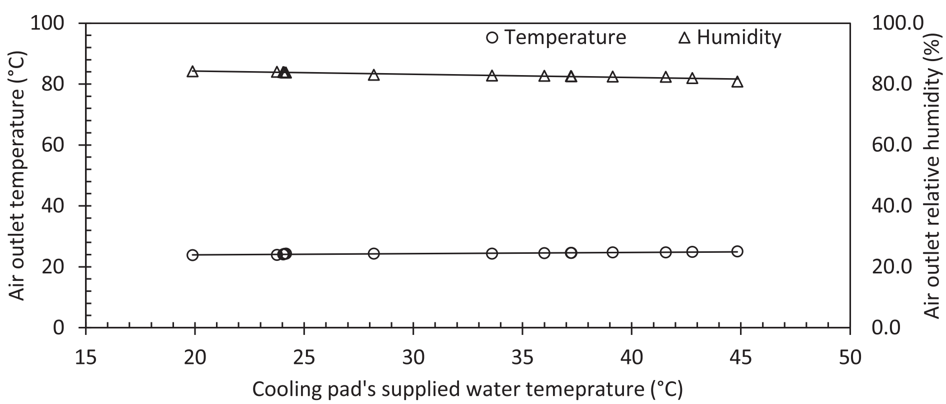
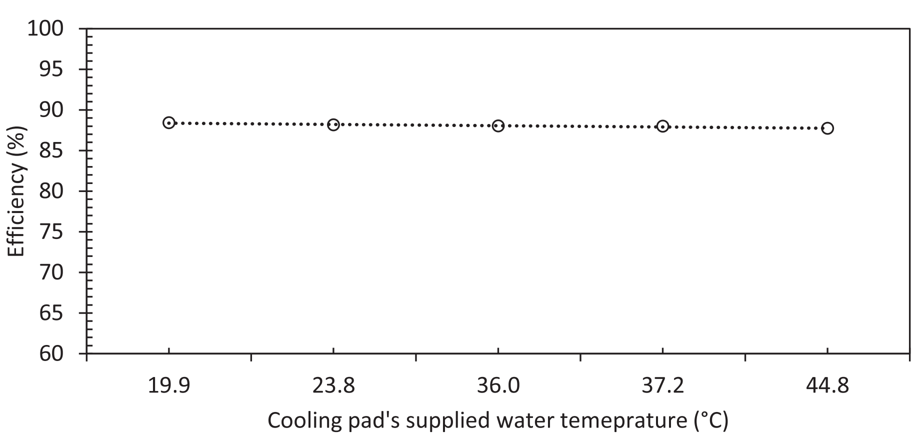


Fig. 6. Experimental setup scheme highlighting EC water temperature impact on cooling performance.



(a)



(b)

Fig. 7. (a) Cooling pad air outlet conditions under its supplied water temperature variation; (b) Cooling pads thermal efficiency under its supplied water temperature variation.

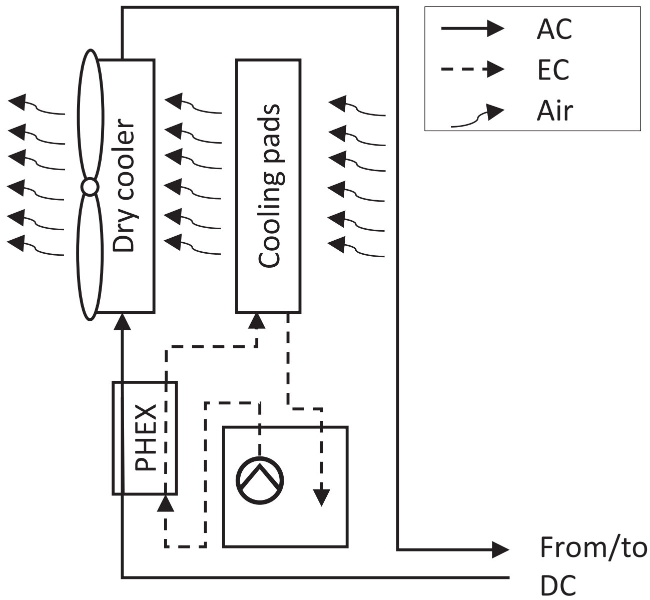


Fig. 8. Optimized IFC+EC architecture.

Table 3
Impact of IFC+EC optimized architecture.

	Original	Optimized IFC+EC
Cooling pads air outlet temperature (°C)	24	24
Pads' water inlet temperature (°C)	35	49
PHEX EC water inlet temperature (°C)	-	35
ΔT on the PHEX AC circuit (K)	-	2.5
Thermal power dissipated on the PHEX (kW)	-	18.5

high outside condition (42 °C; 20%). In this case air temperature at the pad's outlet always vary between 24 and 25 °C, showing a stable pad's thermal efficiency between 88% and 90%.

By increasing the fan speed from 2 m/s to 3 m/s (50% RPM to 100% RPM), the pads' outlet temperature increases by 0.6 K whereas the relative humidity tends to decrease about 9%. The pads' thermal efficiency decreases from 97% to 88% thus the evaporation process is less efficient at higher rotation speeds preventing pad's outlet air temperature and humidity from reaching optimal values.

The impact of dirt and leaves sucked by the dry cooler fans is simulated by clogging cooling pad surface by 2.5% of total surface area, an increase in dry cooler's water return temperature by 1 K at 42 °C DC outside temperature. Accordingly, cooling pad's thermal efficiency decreases about 6%. This is due to reduction of contact area between the air and the wet media. This external factor can slightly impact the evaporative cooling performance and a precaution should always be considered: a clean area around the dry cooler (about 5 m) should be guaranteed.

Regarding the increase of pad's water supply temperature, a growth of 21 K of water temperature leads to a 1.24 K increment in air outlet temperature and a decrease of about 3.3% and 2.5% in relative humidity and cooling pad thermal efficiency respectively. This is due to the impact of the sensible heat transfer rate between water and air which is still small compared to the impact of the latent heat exchange process between the two fluids.

These results allowed authors to propose an optimized IFC+EC system with precooling DC supply water before the dry cooler for a 600 kW DC. This precooling process reduces the workload required from the dry cooler giving a reduction of at least 31% of the cooling demand and enhancing dry cooler's lifecycle by reducing fans maintenance, dirt suction and noise emission. In addition, on yearly energy consumption level, this system can reduce DC operation expenses significantly. This will be developed in future works.

CRediT authorship contribution statement

Maalouf Chadi: Conceptualization, Formal analysis, Validation, Visualization, Writing – review & editing. **Hnayno Mohamad:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Chehade Ali:** Conceptualization, Formal analysis, Validation, Visualization, Writing – review & editing, Funding acquisition, Project administration, Resources. **Klaba Henryk:** Conceptualization. **Polidori Guillaume:** Writing – review & editing, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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