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Research paper

Thermal performance and emissions analysis of a new cooling tower prototype

J. Ruiz [a,*], P. Navarro [b], M. Hernández [b], M. Lucas [a], A.S. Kaiser [b]

[a] Departamento de Ingeniería Mecánica y Energía, Universidad Miguel Hernández, Avda. de la Universidad, s/n, 03202 Elche, Spain
[b] Departamento de Ingeniería Térmica y de Fluidos, Universidad Politécnica de Cartagena, Dr. Fleming, s/n, 30202 Cartagena, Spain

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ABSTRACT

The design of a wet cooling tower involves a number of trade-offs including the efficiency of the device to remove waste heat (thermal performance) and environmental aspects (emissions level). This paper deals with the experimental characterisation of a new cooling tower prototype. The novelty of the work relies on the study of a cooling tower designed to avoid the emission of airborne particles to the atmosphere. The experiments were conducted in a pilot plant built ad hoc for this purpose. The sensitive paper method was used in the environmental impact assessment (emissions level). The comparison between the obtained results and those found in the literature for similar cooling towers indicates that performance of the inverted cooling tower in terms of emissions is remarkable: $D = 1.47 \cdot 10^{-6}$ (0.00015% of the circulating water). This value is up to 300 times lower than the limits imposed by several international standards and involves a reduction in terms of emissions ranging from 40.21% to 82.54% compared to commercial towers. The maximum size of the measured escaping droplets is $d_d = 50$ μm, and the Sauter Mean Diameter of the ensemble of droplets is 31.42 μm. Concerning thermal performance, the observed results are more modest. Operating at nominal conditions, the inverted cooling tower cools the water up to 33.5 ° C. The efficiency of the tower is similar to that of a commercial tower equipped with a film-flow distribution system (up to 6.98% better). The difference is larger (41.16% lower) when compared to the same tower equipped with a splash distribution system.

1. Introduction, background and objectives

1.1. Introduction

Evaporative heat rejection systems such as cooling towers have been traditionally used in a wide array of applications including power generation, cooling cycles or industrial processes where large amounts of waste heat is to be removed. The operation principle of water-cooled systems, such as cooling towers, involves direct contact between two fluid streams of water and unsaturated air. Owing to the vapour concentration difference between gas and liquid phases, mass transfer takes place. As a result, water evaporates and cools down, while the air moistens and becomes warmer.

The design of a wet cooling tower involves a number of trade-offs including the efficiency of the device to remove waste heat (thermal performance) and environmental aspects (emissions level). While the thermal performance is linked to the energetic consumption of the system where the cooling tower is working, the emissions level is related to the tower environmental impact.

Enhancing the thermal performance has always been the main interest of cooling towers designers and manufacturers. Many factors, such as cooling tower components (fill, drift eliminators, etc.), water and air flow rates, ambient conditions, and inlet temperature of the water, affect the operation of the tower. Therefore, the cooling performance could be improved by obtaining the optimum values for these parameters. The thermal performance of the tower is mainly affected by the fill, because up to 70% of heat transfer takes place in this element [1]. In this sense, numerous studies focusing on the thermal performance of a wet cooling tower operating under diverse conditions through experimental and theoretical analyses, have been found in the literature.

The accepted indicator of cooling tower performance is the Merkel number, usually determined by the water-to-air mass flow ratio ($\dot{m}_w/\dot{m}_a$). Mirabdolah Lavasani et al. [2] dealt with rotational splash-type fills for a forced draft counter flow wet cooling tower. The obtained experimental results on the thermal performance of the cooling tower showed that higher rotational velocities significantly increased heat rejection from water. Singla et al. [3] performed an experimental

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[*] Corresponding author.
E-mail address: j.ruiz@umh.es (J. Ruiz).

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Nomenclature

a_V	surface area of exchange per unit of volume (m^2 m^{-3})
A	transfer area (m^2)
A_p	sensitive paper area (m^2)
A_T	cooling tower outlet area (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
d	characteristic drop diameter (m)
d_d	drop diameter (m)
D	drift emissions (-)
h	enthalpy (J kg^{-1})
h_D	mass transfer coefficient (kg m^{-2} s^{-1})
h_s	enthalpy of saturated air (J kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{m}_d$	drifted mass flow by area (kg m^{-2} s^{-1})
$\dot{m}_s$	mass flow exiting the cooling tower (kg s^{-1})
Me	Merkel number ($= h_D a_V V / \dot{m}_w$)
n	number of drops
n_p	number of papers
t_{exp}	exposure time (s)
T	temperature (K)
V	volume of the transfer region (m^3)

Greek symbols

ρ	Density (kg m^{-3})
ε	Efficiency correction factor
ϕ	Relative humidity

Subscripts

∞	ambient
a	air
w	water
i	inlet
o	outlet

Abbreviations

TC	Tower Characteristic
CFD	Computational Fluid Dynamics
SP	Sensitive Paper
DE	Drift Eliminator

investigation on the performance of a forced draft cooling tower with an expanded wire mesh fill. The authors developed correlations for the Merkel number with the water-to-air mass flow ratio and optimised the controlling parameters in order to satisfy a given Merkel number using differential evolution. Rahmati et al. [4] carried out an experimental research to analyse the effect of fill stages. The obtained results indicated that coefficient of efficiency is in direct relation with the hot water temperature, number of stages, and air mass flow rate, while it diminishes by increasing the water flow rate. Shahali et al. [5] experimentally studied three different types of PVC fills (with 7, 9, and 18 ribs). The results showed that the water temperature difference and the cooling efficiency increased when adding ribs. Gao et al. [6] conducted an experimental study on the thermal performance of a wet cooling tower with five kinds of layout patterns of fill (including uniform and non-uniform layout patterns). They concluded that the thermal performance of the optimal layout pattern (non-uniform) can enhance by 30% at maximum within the scope of their test. Raj et al. [7] investigated, experimentally, the use of film, glass, and ball fills on the performance of an induced draft wet cooling tower. Various performance parameters were analysed for each of the fills and it was found that tower characteristics of film fills were 18.56% and 15.59% more than that of glass and ball fills. Dmitriev et al. [8] conducted an experimental study concerning the performance of wet cooling tower with a developed fill pack made of the metal plates with perforations. The comparison between the obtained results for the mass transfer coefficient and those found in the literature for other types of fills proved the high performance of the developed fill.

The interaction between cooling water and air required to maximise the rate of evaporation in the cooling tower (enhance thermal performance), often results in the emission of water droplets which have not evaporated during the cooling process and are taken away by the air stream to the atmosphere. This phenomenon is usually regarded as drift.

Drift emissions from cooling towers have been often reported in the literature as potential hazards [9–11] mainly because its ecological and biological effects on the environment. However, human health constitutes the major concern when it comes to drift emissions. Hazardous pathogens, such as Legionella pneumophila, may be present in the tower basin due to inappropriate maintenance [12] and they can be discharged from cooling towers and disperse into the atmosphere. The most common form of transmission of Legionella is inhalation of contaminated aerosols.

According to the annual epidemiological report issued by the European Centre for Disease Prevention and Control for 2019 [13], 11298 cases were reported in the 28 pre-Brexit EU countries. The number of notifications per 100000 population was 2.2, being the highest notification rate ever observed for the EU. In the last five years, the notification rates nearly doubled from 1.4 in 2015 to 2.2 per 100000 population in 2019. Four countries, France, Germany, Italy and Spain, accounted for 71% of all notified cases, although their combined populations only represent approximately 50% of the EU population. This is a very discouraging data since the overall mortality rate of the disease (it depends on the severity of the disease, the appropriateness of initial anti-microbial treatment, the setting where Legionella was acquired, and host factors) lays within 5%–10% according to the World Health Organization.

To avoid the dispersion of airborne aerosols, cooling towers are usually equipped with elements known as drift eliminators to reduce the emission of water droplets into the environment. A drift eliminator, or just an eliminator, operates on the basis of inertial impact. As the air flows through it, centrifugal forces and droplets' inertia modify the droplets' trajectories towards the eliminator walls, where they coalesce and form a liquid film. However, the reduction in the area because of the presence of the eliminator, results in an increased air velocity. This fact hinders the operation of the eliminators since the drag force becomes dominant and it is easier for the water droplets to escape. That is the reason why drift eliminators have been reported in the literature as drift generators [14].

Few works have been found in the literature addressing the analysis of cooling tower drift linked to the tower components. Computational fluid dynamics techniques have become the most preferred approach to analyse the performance of drift eliminators concerning drift. Some examples are the works of Venkatesan et al. [15], Kouhikamali et al. [16], Ruiz et al. [17], González Pedraza et al. [18]. Concerning the experimental characterisation of drift eliminators, the works of Ruiz et al. [19,20,21,22] experimentally analysed the influence of the drift eliminator on the drift emissions and deposition of commercial cooling. Zheng et al. [23] conducted an experimental research to study the performance of a plate-type eliminator.

The bibliographic review carried out has shown that no general design rules for wet cooling towers in terms of overall performance (thermal performance and emissions) are provided. Instead, major efforts have been undertaken to enhance the thermal performance while little attention has been paid to the environmental impact. Hence, the main motivation of the present work was to address this gap in the literature by designing and testing a new cooling tower prototype that avoids the emission of airborne particles to the atmosphere.

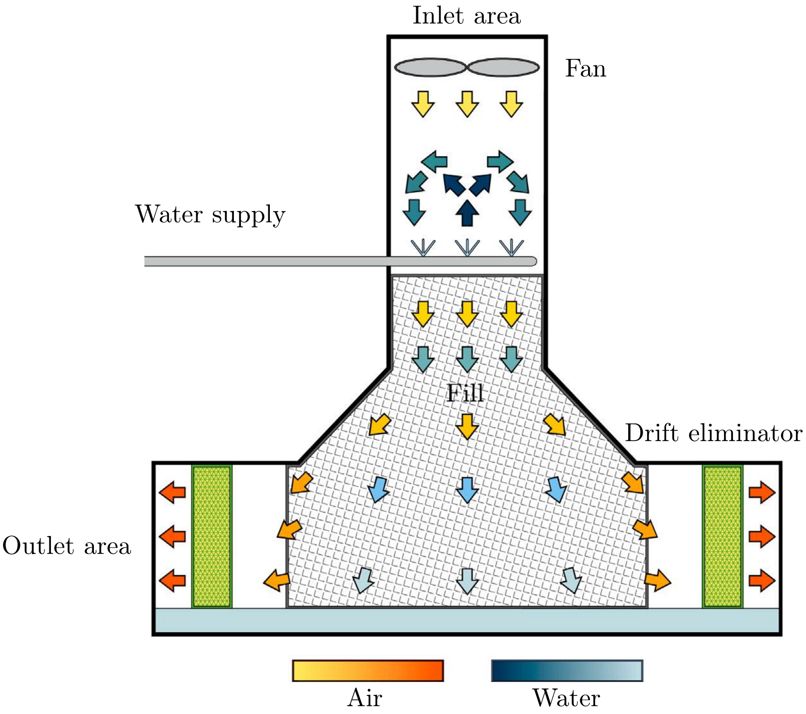

Fig. 1. Schematic of the new prototype of wet cooling tower highlighting the counterflow-parallel flow arrangements and the main parts of the tower.

1.2. Background: the inverted cooling tower

The inverted cooling tower was conceived as an evaporative cooling device able to prevent the dispersion of pollutants to the atmosphere during its operation. The starting hypothesis is that the emissions level would be dramatically reduced by reducing the velocity of the outlet air stream of the cooling tower.

In a conventional cooling tower, the air intake takes place at the bottom of the tower while it is discharged at the top, in contrast to the original design of the inverted cooling tower. As shown in Fig. 1, in the new cooling tower prototype, the air intake takes place at the top of the tower (inlet section, where the axial fan is placed sucking in the outside air). It is then driven downwards to the exit area, which is located at the bottom. By placing the outlet section of the tower at the bottom (near the ground) it can be increased (several times higher than the inlet area) so the air velocity is significantly reduced compared to commercial cooling towers. The path followed by the air is shown by means of the yellow–orange arrows in Fig. 1.

As a consequence, the water droplets entrained by the air stream that have not evaporated, are easy to collect, limiting the system's environmental impact (drift emissions). Besides, the low inertia and the position of the exit area also contribute to lower the environmental impact since the few escaping water droplets will probably be evaporated or deposited on the ground nearby the tower. One of the major drawbacks of this configuration is related to the arrangement of the water and air flows. In conventional cooling towers, water is sprayed downwards, directly opposite to the air flow (counterflow) or perpendicular to it (crossflow). Because of the location of the inlet and outlet sections, the straightforward solution is to spray the water in parallel to the air (downwards). This can result in a lower thermal performance due to the less uniform temperature and concentration differences between the fluids over the entire length of the fluid path. Besides, it can favour drift. To overcome this problem, in the proposed design, water flows upwards from the nozzles to the fan until the inertia and drag forces balance, and then downwards to and through the fill, to finally be collected in the tower basin. The path followed by the water is shown by means of the blue arrows in Fig. 1. Accordingly, the device can be classified as a mechanical forced draft, counterflow-parallel flow, wet cooling tower.

1.3. Objectives

The main objective of this paper was to experimentally characterise the performance of the novel prototype of inverted cooling tower. The experimental setup and the methodology used for thermal performance and drift tests are presented in Section 2. Then, the results obtained in the tests are presented and discussed in Section 3. Finally the most important findings of the study are summarised in Section 4.

2. Experimental methodology

2.1. Test facility

A fully instrumented pilot plant, shown in Fig. 2, was built based on the design described in Section 1.2. All the experimental tests conducted during this research, were performed in this facility, which is located on the roof of the ELDI building, at the Technical University of Cartagena (Cartagena, Spain).

The total height of the tower is 3.5 m. The upper inlet area is square-shaped (0.64×0.64 m^2). An axial fan (Sodeca HEP/EW-63-4/H) is placed at the upper section of the tower, driving the air downwards. The outlet section is rectangular-shaped, $4 \times 3.5 \times 0.7$ m^2 erected at ground level.

The hydraulic circuit is composed of a network of polypropylene pipes. The flow is circulated by a centrifugal pump (Pentax CBT400) from the basin to nine hollow-cone spray nozzles (AX model, Spraying Systems Co. Ltd.) horizontally arranged, where the water is sprayed. The set of nozzles is located 1.2 m downwards the fan. The trickle-type fill is set between the water nozzles (1.6 m long) and the tower basin and the thermal load consists of a conventional boiler of 45 kW nominal power (Gabarrón CPE45). The flow rates of water and air can be changed by two variable frequency drives connected to the pump and the fan, respectively. Besides, the water mass flow rate can be manually changed by a balancing valve.

Fig. 3 shows a schematic representation of the pilot plant shown in Fig. 2 including all the sensors used during the experiments. They were used to record and to monitor the variables required to experimentally characterise the thermal performance of the tower. The environmental conditions (ambient air temperature, air relative humidity, wind

Table 1
Sensor devices specifications.

Measurement	Measuring device	Brand	Model	Range	Accuracy
Air velocity	Hot wire anemometer	Distech	PDCSY-AV-622	0–32 m s^{-1}	±3%
Air temperature	Thermohygrometer	Siemens	QFM3160	−40–70 °C	±0.6 °C
Air humidity				0–100%	±2%
Water flow rate	Electromagnetic flowmeter	Krohne	OPTIFLUX 1000	−12–12 m^3 s^{-1}	±0.5%
Water temperature	RTD-Pt1000	Siemens	QAE2164.010	−10–120 °C	±0.1%

Fig. 2. Built prototype of the inverted cooling tower.

speed and wind direction) were measured with a meteorological station placed on our laboratory roof just beside the experimental facility (Davis Vantage Pro2). The variables related to the thermal performance of the system can be divided into air and water measurements. Concerning air measurements, air velocity, temperature and relative humidity were measured at the inlet and outlet sections of the cooling tower. Eight hot wire anemometers were placed in the centre of each one of the faces of the inlet–outlet sections. In the case of the temperature and relative humidity, five thermo-hygrometers were used: four in the outlet sections and one in the inlet section. The inlet and outlet water temperatures in the circuit were registered in the discharge of the tower basin and in the inlet of the distribution system. The air flow rate was calculated by using the average velocity and the specific volume of inlet air along the inlet section of the tower, while the water flow rate was measured using an electromagnetic flowmeter. Table 1 contains the main specifications of the sensors: brand, model, measuring range and accuracy. The range of the sensors encompasses the upper and lower limits of the operating conditions of the tower. The sensors accuracy is used to calculate the experimental uncertainty values for the Merkel number and the water-to-air mass flow ratio. The data was recorded by a ECLYPSE control unit (Distech).

2.2. Thermal performance tests

As previously stated in Section 1.1, it is accepted in the literature that, the performance of a wet cooling tower can be measured by the well-known Merkel number. This dimensionless number measures the degree of difficulty of the mass transfer processes taken place in the cooling tower exchange area. According to the Merkel theory for the performance evaluation of wet cooling towers [24], the Merkel number can be calculated as shown in Eq. (1),

$$\mathrm{Me} = \frac{h_D A}{\dot{m}_w} = \frac{h_D a_V V}{\dot{m}_w} = \int_{T_{w_o}}^{T_{w_i}} \frac{c_{p_w}}{h_{s_w} - h} dT_w \tag{1}$$

In the literature, this performance coefficient can also be defined as KaV/L, where $K = h_D$, $a = a_V$ and $L = \dot{m}_w$ or just Tower Characteristic, TC. The Merkel number measures the degree of difficulty of the mass transfer processes taken place in the cooling tower exchange area since the potential for heat and mass transfer at a particular water temperature is the difference between h_{s_w} and h.

The right-hand side of Eq. (1) can be solved if the water inlet temperature, water outlet temperature, air inlet dry-bulb temperature, air inlet wet-bulb temperature, water mass flow rate and airflow rate are known. However, the evaluation of the integral is not self-sufficient so it does not lend itself to direct mathematical solution and needs to be evaluated by numerical integration. The four-point Chebyshev integration technique is recommended by several internationals standards to determine Me. If two intervals are used in conjunction with the trapezoidal rule, the integral, or Merkel number is given by,

$$\mathrm{Me} = \int_{T_{w_o}}^{T_{w_i}} \frac{c_{p_w}}{h_{s_w} - h} dT_w \approx c_{p_w} \frac{\left(T_{w_i} - T_{w_o}\right)}{4} \sum_{j=1}^{4} \frac{1}{\left(h_{s_w} - h\right)_j} \tag{2}$$

Six sets of experiments regarding thermal performance were conducted during this investigation. The different levels for the water-to-air mass flow ratio were obtained by modifying the air mass flow rate into different levels (changing the frequency of the variable frequency drive) while maintaining the water mass flow rate equal to $\dot{m}_w \approx 1$ kg s^{-1}. As a result, the range for the experimental $\dot{m}_w/\dot{m}_a$ values was in the range of 0.2–0.7. The thermal load was fixed to 15 kW in all the tests.

The standards UNE 13741 “Thermal performance acceptance testing of mechanical draft series wet cooling towers” [25], and CTI “Acceptance Test Code for Water Cooling Towers” [26] were taken as a reference to evaluate the stationary conditions of the tests.

2.3. Drift tests

To experimentally measure the emissions from the tower, the Sensitive Paper (SP) method was employed. This method is classified as a sensitised surface method by the Isokinetic Drift Test Code ATC 140 [27]. Its principle of operation relies on the detection of the droplets by inertial impact onto a chemically treated surface. Impacting drops leave a blue clear stain on the yellow paper background, which is proportional to the droplet original speed, diameter, and angle of attack. Owing to its low price, ability to perform on-site measurements, and capability of providing the drop size distribution data, the method perfectly suited the purpose of this investigation. The following stages were covered to calculate the drift emissions using the SP method:

1. Stage 1: Conducting the experimental tests.
2. Stage 2: Extracting the information from the papers by means of image processing techniques.
3. Stage 3: Drop size distributions/drift calculation.

At stage 1, by means of a papers carrier (five PVC plates with four papers on each plate), twenty sensitive papers were exposed to the air stream in each of the tower outlet surfaces, Fig. 4. Each outlet area was divided into twenty equal quadrants covering the same portion of the surface and the papers were placed at the centre of each quadrant. The papers used in the experiments were sized 76 × 52 mm.

The coated side of the papers was exposed to the air stream against the flow direction during a exposure time of 4 min (240 s). Normally, this time is set as a trade-off between over-occupancy of drops and

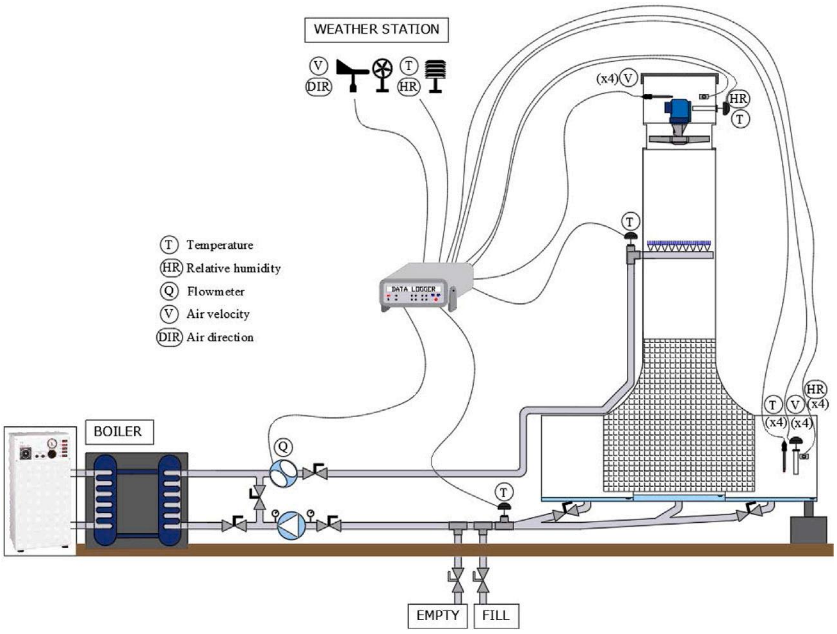

Fig. 3. Schematic of the novel mechanical forced draft wet cooling tower.

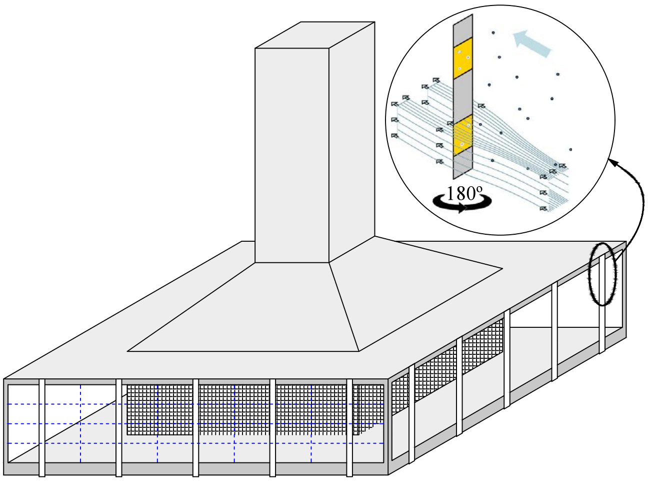

Fig. 4. Positions of measurement in the cooling tower exit area.

paper edges becoming green due to the moist air flow. In the case of the inverted cooling tower, and due to the low level of drift emissions, the over-occupancy of droplets was not a problem and the exposure time was set according to the second criterion. After expiry of the exposure time, the PVC plates were withdrawn back.

At stage 2, a high-resolution scanner was used to digitise the sensitive papers. The software DRIFT© was used to extract the recorded information from the scanned papers. This software was developed by the group of scientists who conducted this research and it is based on the digital software platform described in Ruiz et al. [19]. This methodology has been applied in several investigations related to cooling tower drift measurements and drop size distribution characterisation [20–22,28]. The software operates as follows. First, all the stains present in the paper are detected by using the well-known Canny edge detector. Next, the stains are filtered and classified. The idea behind this procedure is to consider only the stains coming from real drops and discard those otherwise (i.e. paper background stains, fibres, etc.). Performing the filtering and the classification involve gathering information concerning physical features of the stains, such as the roundness or the Hu moments [19], and using it to describe them. To design the classification algorithm, a training data set of 3000 samples (stains) was extracted from the papers and was classified manually. The resulting classifier (decision tree) was able to filter and classify the stains that have their origin in real drops with a success rate of 95%. As a result, the software provides the number of real drops count per diameter size. A correction factor accounting for the drop-stain relationship is applied during this stage.

According to the methodology, the uncertainty of the digital image processing is determined to be ±2 pixel of the original diameter (±5.29 μm for 4800 dpi resolution). Hence, the smaller the droplet diameter, the higher the experimental uncertainty. This point is of high importance.

According to the sensitive paper manufacturer and the CTI standard ATC-140 [27], sensitised surface methods provide reliable droplet size characteristics above 30 μm. In previous investigations [22], it was concluded that the method provided the droplet diameter within a reasonable uncertainty for diameters larger than 25 μm. A manual supervision of a set of more than 1000 droplets (registered by different papers) showed that the great majority of the stains whose diameter was below 25 μm, were not real droplets. Accordingly, an experimental threshold $d_d \geq 25\ \mu\text{m}$ was set in order to ensure the reliability of the results.

Finally, at stage 3, the drop size distribution data and the amount of drift are calculated. Drift emissions are obtained by using the set of Eqs. (3), (4) and (5). The drifted mass flow by unit of surface, $\dot{m}_d$, refers to the mass flow exiting the tower at the portion of the surface covered by each one of the exposed papers. It is calculated according to Eq. (3) and, at this step, water droplets are considered to be perfect spheres of diameter d_d. These results include the efficiency correction factor (ε) to account for the drops originally present in the air stream which have not ended up impacting on the paper due to their inertia. The total drifted mass flow, $\dot{m}_s$, is the total mass flow of water droplets exiting the tower. It is calculated by multiplying the mass flow by unit of surface to the area covered by the paper. In the case that the papers are equally distributed at the exit section of the cooling tower (each paper covering the same area), $\dot{m}_s$ can be calculated as in Eq. (4). Finally, the drift emissions, D, are computed as a fraction of the circulated water flow $\dot{m}_w$, Eq. (5).

$$\dot{m}_{d_j} = \frac{\rho_w \pi}{6 A_p t_{\exp}} \sum_{i=1}^{N} d_{d_i}^3 \varepsilon_i^{-1} \tag{3}$$

Table 2
Averaged values in the thermal experimental test runs conducted.

Test run	T_∞ (°C)	ϕ_∞ (%)	T_{w_i} (°C)	T_{w_o} (°C)	$\dot{m}_w$ (kg s^{-1})	$\dot{m}_a$ (kg s^{-1})
1	27.32	46.25	28.09	23.51	0.9760	4.649
2	28.01	66.83	31.68	26.79	0.9069	4.611
3	27.05	70.02	30.79	26.35	1.010	4.869
4	25.44	70.13	31.74	27.43	1.009	1.627
5	26.25	72.52	32.55	28.16	1.008	2.100
6	23.95	67.77	31.30	27.07	1.011	1.378

$$\dot{m}_s = \frac{A_T}{n_p}\sum_{j=1}^{n_p}\dot{m}_{d_j} \tag{4}$$

$$D = \frac{\dot{m}_s}{\dot{m}_w} \tag{5}$$

Drift tests were performed in nominal conditions (fan and pump operating at 50 Hz). Three sets of experiments were carried out to ensure repeatability. It is worth mentioning that the tests were conducted in windless conditions to discard the influence of the wind speed on the drift results. Eighty sensitive papers were exposed to the air stream during 4 min in each test (20 papers per face).

3. Results and discussion

3.1. Thermal performance

This section includes the results for the cooling tower thermal performance characterisation. As outlined in Section 2.2, six sets of experiments were carried out. Table 2 shows the averaged values of the most relevant ambient and operating conditions during the tests. As it can be seen, the different levels for the water-to-air mass flow ratio required to characterise the thermal performance, were obtained by modifying the air mass flow rate into different levels while maintaining the water mass flow rate. The ambient conditions registered during the tests ranged from 24 °C to 28 °C (ambient temperature) and from 46% to 72% (ambient relative humidity).

The experimental results obtained for the variation of the Merkel number with the water-to-air mass flow ratio, for the novel design of cooling tower, are presented in Fig. 5. The Me $-\dot{m}_w/\dot{m}_a$ relationship is a linear function on log–log scale. This involves that the effect of $\dot{m}_w/\dot{m}_a$ on Me becomes less pronounced as $\dot{m}_w/\dot{m}_a$ increases. This behaviour is attributed to the decrease in the fraction of water that evaporates per unit of inlet water with increasing $\dot{m}_w/\dot{m}_a$ values. The situation corresponding to the minimum $\dot{m}_w/\dot{m}_a$ can be interpreted as the maximum air flow rate for a given water flow rate to be cooled. This results in the maximum driving force and, therefore, maximum Merkel number. As $\dot{m}_a$ decreases progressively, the driving force decreases for a given $\dot{m}_w$, and Me decreases accordingly.

The maximum and mean experimental uncertainty values for the Merkel number and the water-to-air mass flow ratio are 6.79% and 6.38%, and 1.82% and 1.81%, respectively. They were calculated according to the ISO Guide [29] (type B evaluation for standard uncertainty and level of confidence of 95% for the expanded uncertainty) with the sensor specifications shown in Table 1.

As extensively reported in the literature [30,31], the transfer coefficient of the tower can be correlated in its simplest form as a function of the water-to-air mass flow ratio, as in Eq. (6).

$$\mathrm{Me} = c\left(\frac{\dot{m}_w}{\dot{m}_a}\right)^{-n} \tag{6}$$

The solid line in Fig. 5 corresponds to the transfer characteristic of the cooling tower, described by Eq. (6), and the values obtained for constants c and n, obtained by linear regression, are $c = 0.4913$ and $n = 0.3435$ ($R^2 = 0.974$).

Having reliable correlations validated against experimental data can be used with several purposes, such as designing, sizing or selecting cooling tower components. They can also be used to analyse and optimise the operating conditions of a cooling tower in terms of energetic performance. In this work, the information regarding the transfer coefficient is used in the cooling tower analysis to predict the water outlet temperature. The results of the comparisons between calculated and measured outlet water temperatures are displayed in Fig. 6. As it can be observed, the predicted results are remarkably confident since the maximum and averaged differences between experimental and predicted results are 0.18 °C and 0.07 °C, respectively. This translates into a maximum percentage difference of 0.7% (~0.3% on average).

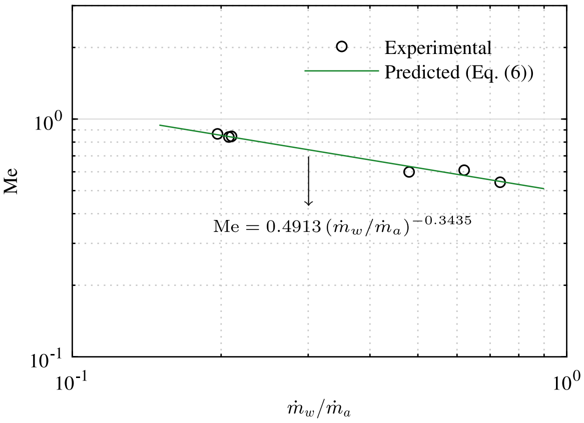

Fig. 5. Experimental results for the Me number as a function of $\dot{m}_w/\dot{m}_a$.

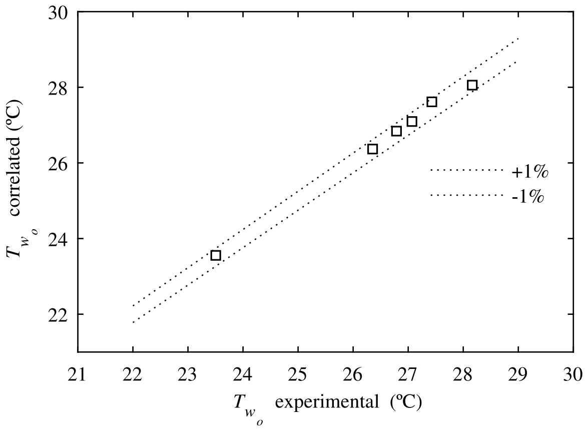

Fig. 6. Comparison between experimental and predicted cooling tower outlet water temperatures.

3.2. Drift

This section includes the results for the cooling tower emissions characterisation. The average ambient conditions during the tests are summarised in Table 3.

The results obtained in the experiments were considered repeatable since the data from the 3 individual tests conducted did not deviate

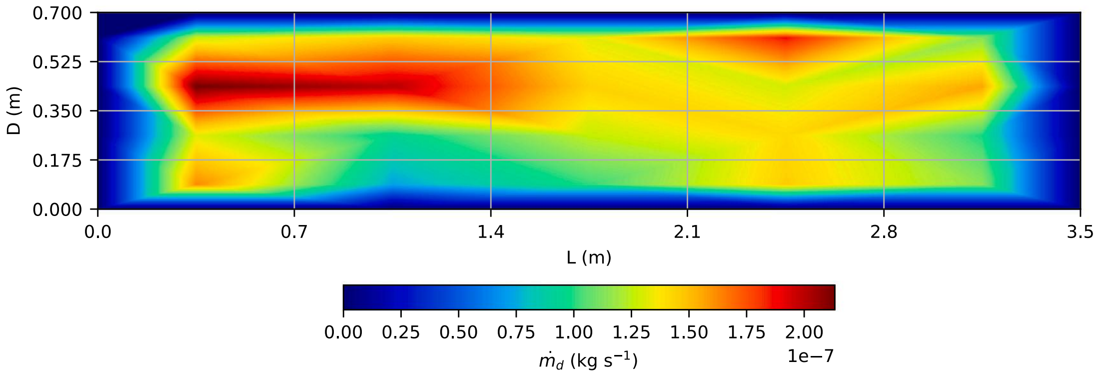

Fig. 7. Experimental results (colourmap) for the drifted mass flow rate measured in the different papers exposed at the eastern outlet surface.

Table 3
Averaged values in the experimental drift tests conducted.

T_∞ (°C)	ϕ_∞ (%)	T_{w_i} (°C)	v_{a_o} (m s^{-1})	$\dot{m}_w$ (kg s^{-1})	$\dot{m}_a$ (kg s^{-1})
24.40	66.00	27.14	1.089	1.012	5.184

Table 4
Experimental results for the drifted mass flow rate measured in the different papers exposed at the eastern outlet surface.

$\dot{m}_d \times 10^7$ (kg s^{-1} m^{-2})					
Paper/Plate	1	2	3	4	5
1	1.2795	1.4604	1.3250	1.8726	1.1423
2	2.1393	2.0022	1.4421	1.2924	1.5598
3	1.3249	0.9303	1.2592	1.4172	0.9883
4	1.6204	0.7348	1.0082	1.4511	1.1432

by more than 7%. Hence, the results for one experimental test are described here to keep the coherency of the paper.

Table 4 shows, as an example, the results for $\dot{m}_d$ (mass flow exiting the tower at the portion of the surface covered by each one of the exposed papers) calculated as per Eq. (3) for the 20 papers exposed in one outlet area (eastern outlet surface). It can be observed that the drift by unit of area is homogeneous in the tower exit section. The order of magnitude is $\dot{m}_d \sim 10^{-7}$ kg s^{-1} m^{-2}. The variations for this parameter can be justified by the non-uniformity of the water distributed over the fill. Fig. 7 shows the experimental drift colourmap for the eastern outlet area of the cooling tower. Here the cooling tower exit surface, divided into the twenty subdivisions where the papers are located, is coloured depending on the $\dot{m}_d$ value. The level of escaped mass flow by unit of area for points outside the experimental measurements was calculated by means of a linear interpolation.

The calculated value for the amount of water escaped from the tower $\dot{m}_s = 1.4618 \cdot 10^{-6}$ kg s^{-1}, which corresponds to $D = 1.47 \cdot 10^{-6}$ (0.00015%).

The SP method provides the drop size distributions at the outlet area of the cooling tower. In this sense, Fig. 8 depicts the histogram, and experimental cumulative mass distribution (distribution curve that gives measured cumulative mass fraction data as a function of drop diameters) for the droplets collected by the 80 papers exposed. As it can be seen in the histogram, the whole ensemble of the droplets at the cooling tower exit surface, is sized $d_d \leq 50$ µm. This leads to an arithmetic mean diameter of $d_{10} = 29.55$ µm and a Sauter mean diameter of $d_{32} = 31.42$ µm. Both characteristic diameters were calculated according to the general mean diameter expression shown in Eq. (7).

$$d_{pq} = \left[\frac{\sum_{i=1}^{N} n_i d_{d,i}^{p}}{\sum_{i=1}^{N} n_i d_{d,i}^{q}} \right]^{\left(\frac{1}{p-q}\right)} \tag{7}$$

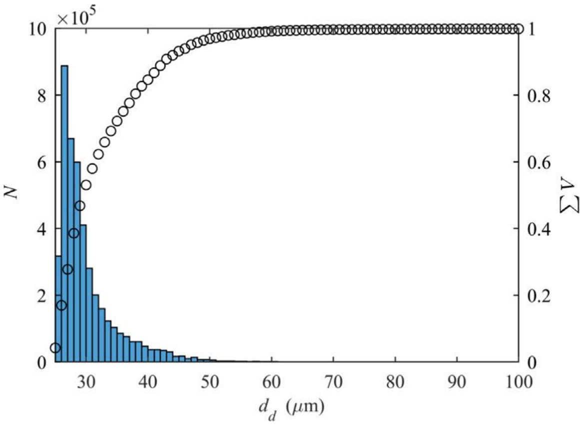

Fig. 8. Experimental droplet distribution results. Histogram (left) and cumulative mass distribution (right).

The small value for the characteristic diameter can be attributed to the water and air flow arrangements. Most of the water droplets sprayed by the high-pressure nozzles in the distribution system are evaporated during the counterflow-parallel path followed by the water, and only the droplets with low inertia (diameter) are able to follow the 90-degrees-curved air streamlines inside the tower. The fact that the entrained droplets have a small characteristic diameter (~ 30 µm) alongside with the low air velocity level at the outlet section of the tower (~ 1 m s^{-1}), implies that the new cooling tower prototype has little environmental impact: not only the drift rate is low but also the size of the droplets escaping the tower is small. The few escaping droplets will probably be evaporated or deposited on the ground nearby the tower.

3.3. Comparison with experimental data available in the literature

To assess the relative performance of the tower, the comparison of the observed results in this research with some results previously published in the literature by the same group of researchers involved in the current investigation, is presented in this section.

The performance of the tower is compared to that of a commercial forced, mechanical-draft, film-fill type, wet cooling tower with a nominal capacity of 30 kW. The thermal performance of this commercial cooling tower was analysed by Lucas et al. [32,33], where the Merkel number was experimentally calculated when the tower was fitted with six different drift eliminators (referred to as drift eliminator (DE) A–F in the paper) and a two types of water distribution systems (film-flow and splash types). The performance in terms of emissions, was reported by Ruiz et al. [21]. The drift rates of the tower, equipped with the same

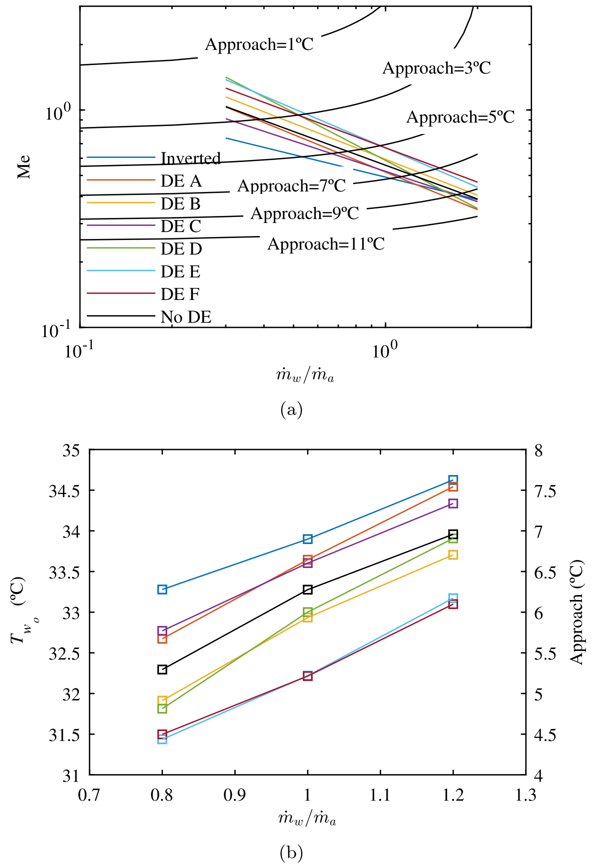

Fig. 9. Comparison between the experimental data obtained in this research and the data reported in the literature. (a) Me number and (b) T_{w_o} for the stated conditions. DE stands for Drift Eliminator in the figure legend and the eliminator types (A–F) are described in Lucas et al. [33]. Design conditions: 27 °C of wet-bulb temperature and 5 °C of range.

eliminators and distribution systems described above, are presented in this reference.

Fig. 9 presents the thermal performance comparison with the film-flow distribution system. Fig. 9(a) shows the Merkel number comparison. The curves for the different drift eliminators have been plotted against curves of different constant approaches.

The cooling tower approach is defined as the difference between the cooling tower outlet cold water temperature and the ambient wet bulb temperature. It is, therefore, a good indicator of the cooling tower performance. The constant approach curves were calculated for the design operating conditions of both cooling towers: 27 °C of wet-bulb temperature and a 5 °C of range, defined as the difference between the cooling tower water inlet and outlet temperatures.

The shape of the constant approach curves is determined by the $\dot{m}_w/\dot{m}_a$ value. The imaginary situation corresponding to an infinite air rate results in $\dot{m}_w/\dot{m}_a = 0$. This results in the maximum driving force and the minimum required Merkel number. As the air rate decreases progressively, the driving force decreases and the required Me increases. The points of intersection between the constant approach curves and the tower performance curves (Eq. (6)) indicate the $\dot{m}_w/\dot{m}_a$ values at which the towers will operate at the given conditions. Concerning the Me comparison, the performance of the inverted cooling tower is lower than the commercial cooling tower for the low water-to-air mass flow rates (up to $\dot{m}_w/\dot{m}_a \sim 1.5$). The inverted tower performs, on average, 19.40% worse than the commercial tower in the above mentioned range. For high water-to-air mass flow rates ($1.5 \leq \dot{m}_w/\dot{m}_a \leq 2$), the novel design performs 6.98% better than the commercial tower fitted with eliminators A, C and D in Lucas et al. [33]. The difference is larger when compared to the splash distribution system (not included in Fig. 9), average of 41.16% lower.

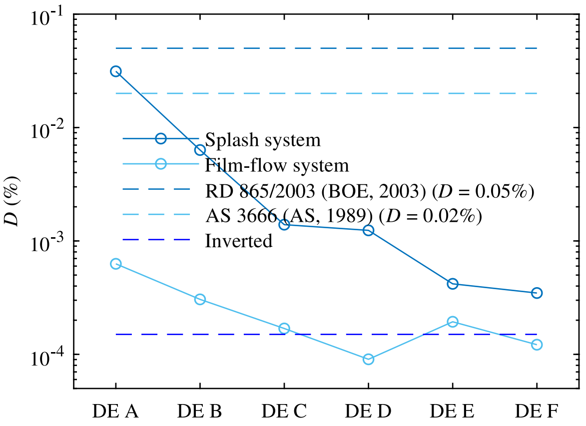

Fig. 10. Comparison between the drift emissions from the inverted cooling tower and bibliographic results [21] and international standards.

Although the Merkel number is the best indicator to compare the performance of different wet cooling towers, the energetic implications derived from the use of this dimensionless parameter can be somehow not straightforward. The key parameter to predict the performance of the system where the cooling tower is removing heat from (power cycle, refrigeration cycle, etc.) is the outlet water temperature. Hence, the predicted outlet water temperatures for the bibliographic results mentioned above and for 3 different levels of $\dot{m}_w/\dot{m}_a$ (0.8, 1, and 1.2) are presented in Fig. 9(b). These temperatures were calculated using the design conditions for both towers alongside with the correlations concerning the transfer coefficients shown in Eq. (6) and those reported in the literature. For example, taking the inverted cooling tower and a water-to-air mass flow ratio equal to one, an approach of ≈ 7 °C is obtained. This translates into a water output temperature of ≈ 34 °C.

Fig. 10 shows the drift emissions comparison. This figure also includes the drift limits imposed by some international regulations, Royal Decree RD 865/2003 [34] in Spain (0.05%) and Australian Standard AS/NZS 3666 [35] in Australia (0.02%). The AP-42 [36] also provides a drift rate of 0.02% for induced, mechanical draft, wet cooling towers.

The calculated drift values for the inverted cooling tower are well below the above mentioned standards (130 and 330 times). The drift emissions are 82.54% lower than those of the commercial cooling tower fitted with the splash system. When the film-flow system is equipped in the tower, emissions can be reduced to 40.21% on average, with the exception of eliminators D and F, for which the order of magnitude is the same.

Although quantitatively speaking, the inverted tower performs similarly than the commercial cooling tower fitted with the film-flow system, qualitatively there is a huge difference related to the size of the droplets escaping the tower. A film-flow water distribution system consists of an open channel, which, once is filled, spills out the water over the fill. Accordingly the droplets entrained by the air stream have higher diameters than if they would have been broken up into small particles due to the higher pressure level reached in the nozzles of a splash system. Besides, the location of the outlet section and the high air velocity level in this area involve that the water droplets taken away by the air stream will travel long distances, increasing the area affected by the tower in terms of environmental impact, contrary to what happens in the new cooling tower prototype.

4. Conclusions

This study has enabled the investigation of the thermal performance and the drift emissions of a novel design of mechanical-draft, wet cooling tower which aims to reduce the environmental and health impact usually related to evaporative cooling devices. The results obtained during the investigation can be summarised as follows:

- The new cooling towers prototype achieves 0.00015% drift rate. This value is up to 300 times lower than the limits imposed by several international standards concerning drift. The size of the measured escaping droplets is smaller than for commercial cooling towers: maximum size of 50 μm and Sauter Mean Diameter of the ensemble of droplets of 31.42 μm. Given the observed emission level and the size of the droplets escaping the tower, the device can be termed as a nearly-zero emissions cooling tower.
- Concerning thermal performance, the inverted cooling tower cools the water up to 33.5 °C (design conditions). The efficiency of the tower is up to 6.98% better to that of a commercial tower equipped with a film-flow distribution system. The difference is larger (41.16% lower) when compared to the same tower equipped with a splash distribution system.
- The performance of the inverted cooling tower is similar to that of a commercial cooling tower of the same capacity and design conditions equipped with a film-flow water distribution system. Despite the lower thermal performance compared to a commercial cooling tower equipped with a splash water distribution system, the benefits of the inverted cooling tower are two-fold. On the one hand, the thermal performance can be increased by modifying the design. On the other hand, the arrangement of the outlet area and the characteristic size of the ensemble of droplets leaving the tower favours the evaporation nearby the tower, reducing the affected area in terms of environmental impact.

4.1. Recommendations and future research

To obtain an unequivocal criterion for cooling tower design/selection, the correlations derived in this paper for the thermal performance and the data concerning emissions, should be included in a global energetic model considering the specific application where the cooling tower is operating and the ambient conditions. The global results for energy consumption and water use constitute reliable comparative data between different cooling towers.

Forthcoming investigations must aim to improve the thermal capacity of the cooling tower and enhance its performance to acceptable levels, while maintaining the emissions rate. In this sense, the physical configuration of the tower that affect the transfer processes taken place in the exchange area of the tower must be analysed. The nozzles and fill position are pointed out as the modifications which can be adopted straightforward. Additionally, the pump and fan should be carefully selected to achieve a conventional operation point in terms of water-to-air mass flow ratio.

CRediT authorship contribution statement

J. Ruiz: Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition. **P. Navarro:** Software, Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **M. Hernández:** Conceptualization, Investigation, Formal analysis. **M. Lucas:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **A.S. Kaiser:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

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.

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