Energy and Buildings 125 (2016) 181–195

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Experimental study of drift deposition from mechanical draft cooling towers in urban environments

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ARTICLE INFO

Article history:
Received 29 March 2016
Received in revised form 28 April 2016
Accepted 29 April 2016
Available online 2 May 2016

Keywords:
Cooling tower
Drift
Deposition
Legionella

ABSTRACT

Cooling towers are evaporative devices for removing heat in several applications such as air conditioning in buildings and industrial processes. In this work a comprehensive experiment to study the drift deposition from a mechanical draft cooling tower located in an urban environment was conducted, because of the lack of data in the literature. To predict the area affected by the cooling tower drift deposition is interesting both for its environmental impact assessment, and for the detection of the origin of an outbreak of Legionnaire's disease. The objective of the experiment was the measurement of the amount of drift water emitted and deposited from the cooling tower. Secondary objectives were to establish a database for use in drift deposition model validation and to analyze the interaction between ambient variables on downwind deposition. These objectives were met by the simultaneous measurement of cooling tower source emission parameters, meteorological variables (registered by a 40 m tall meteorological tower) and drift deposition during four test runs. The sensitive paper technique was employed. Regarding downwind deposition patterns, deposited water and characteristic droplet size decreased as the distance from the tower increased. Variations of 70% of deposited water were found in the measurements at close distances to the tower when the wind velocity level was low. Wind direction also affected the deposition level. Averaged differences of about 45% were observed between the results obtained for the wind blowing from the northwest or the southeast.

1. Introduction

Cooling towers constitute an energy-efficient solution for the dissipation of waste heat from power plants, air conditioning and industrial processes. However, some questions concerning their potential environmental impact have emerged in recent decades. In an evaporative cooling tower, a minute fraction of the circulation water is carried out of the tower in the form of small droplets, which is called drift. Cooling tower drift is objectionable for several reasons such as ensuing corrosion problems on equipment, piping and structural steel, accumulated salts on downwind vegetation, ice formation during winter months and even the placement of salts and corrosive chemicals on the surface of cars and car windows in parking lots [1]. The most hazardous problem related to human health is the emission of chemicals or microorganisms into the atmosphere. Regarding microorganisms, the most well-known pathogens are the multiple species of bacteria collectively known as Legionella [2].

The dispersion and deposition of particles in the vicinity of buildings is one of the main issues related to cooling towers operation in urban environments. The use of a model that predicts the area affected by the cooling tower drift deposition is interesting both for its environmental impact assessment, and for the detection of the origin of an outbreak of Legionnaire's disease. Wilmot et al. [3] established a Bayesian Belief Network to model the uncertainty of aerosols released from cooling towers and a Geographic Information System to create a wind dispersion model and identify potential cooling towers as the source of infection. They constructed a binormal plume dispersion model to update the probability of a cooling tower infection given a case of Legionella. Brown et al. [4] presented an epidemiological method to calculate dose of exposure to a source of Legionnaire's disease infection. They defined a variable, called Aerosol Exposure Units ($AEU = tD^{-1}$), which related the time (t) spent at distance (D) from the source. Both references carried out a simple, and therefore limited, simulation of the cooling tower drift dispersion.

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http://dx.doi.org/10.1016/j.enbuild.2016.04.076
0378-7788/

Nomenclature

A_p	sensitive paper surface (m^2)
A_T	cooling tower exit surface (m^2)
$\mathcal{A}$	constants for downwind deposition levels prediction
$d_{0,5}$	drop distribution characteristic diameter (m)
d_d	drop diameter (m)
d_s	stain diameter (m)
D	distance from the source (m)
D	cooling tower drift (%)
$\mathcal{D}$	constants for characteristic diameter levels prediction
$\mathcal{E}$	constants for characteristic diameter levels prediction
$\mathcal{F}$	constants for characteristic diameter levels prediction
$\dot{m}_d$	mass flow measured by the sensitive paper ($kg\,s^{-1}\,m^{-2}$)
$\dot{m}_s$	mass flow exiting the cooling tower ($kg\,s^{-1}$)
$\dot{m}_w$	mass flow sprayed by the cooling tower ($kg\,s^{-1}$)
n_p	number of papers placed at the cooling tower exit surface
n_p^d	number of papers placed on the ground
N	number of drops
t	time (s)
t	ambient temperature (°C)
$t_{z=0}$	y-intercept for t linear regression (°C)
$t_{\exp}$	exposure time (s)
u_τ	friction velocity ($m\,s^{-1}$)
v	ambient wind velocity ($m\,s^{-1}$)
z	height (m)
z_0	ground roughness (m)

Greek symbols

α	slope for t linear regression (°C m^{-1})
β	slope for ϕ linear regression (% m^{-1})
ε	collection efficiency
κ	von Kármán constant (= 0.41)
λ	log-normal mean value
ϕ	ambient relative humidity (%)
$\phi_{z=0}$	y-intercept for ϕ linear regression (%)
ρ	density ($kg\,m^{-3}$)
$\sum V$	accumulated water volume (m^3)
σ	log-normal standard deviation
θ	difference between the angle of the considered cord and the angle of the main cord (°C)

Subscripts

a	air
w	water

Abbreviations

AEU	aerosol exposure units
CFD	computational fluid dynamics
NW	northwest
SE	southeast
SP	sensitive paper

The movement of gases and fine aerosols from cooling tower exits can be predicted by analytic procedures. Chen and Hanna [5] compared 10 drift deposition models using a set of standard input conditions for a natural draft-cooling tower. They concluded that most of the models agreed within a factor of 3. However, when all 10 models were compared, the predicted maximum drift deposition rates differed by two orders of magnitude. Besides, the downwind locations of the maximum differed by one order of magnitude. Policastro et al. [6] compared most of the same drift deposition models with the experimental data. They concluded "none of the existing models performed well". Policastro et al. [7] developed the SACTI model specifically to improve drift prediction and they concluded that for a model to predict within a factor of 3 of measured data could be considered a successful prediction. Unfortunately, neither of these approaches allows for the influence of nearby large buildings on the flow fields, which affect the local building downwash and the cooling tower drift.

Computational Fluid Dynamics (CFD) techniques constitute a second approach to estimate cooling tower drift and deposition. CFD is based on solving the relevant equations of motion by numerical methods. Recent improvements in numerical procedures and in computers now make it possible to calculate reasonably large and complicated domains of atmospheric motions in complex urban settings. Bergstrom et al. [8] reported the results of a two-dimensional simulation of the interaction of the flow through an idealized cooling tower with the wind flow over the tower. Takata et al. [9] calculated the effects of wind on the visible envelope of moist cooling tower plumes using CFD. Bornoff and Mokhtarzadeh-Dehghan [10] presented the results of a numerical investigation into the interaction of two adjacent plumes in a cross-flow. Riddle et al. [11] compared their CFD results with the predictions from the Atmospheric Dispersion Modelling System in geometrically complex situations such as the case of buildings in close proximity. Alkhedhair et al. [12] presented a numerical investigation of inlet air pre-cooling water spray to enhance the performance in Natural Draft Dry Cooling Towers.

A reference found in the literature that specifically addresses the problem of drift deposition using CFD is done by Meroney [13]. He developed a CFD model to simulate natural draft cooling tower plume dispersion and drift. This author predicted drift deposition levels downwind a cooling tower. The simulation replicated the Chalk Point Dye Tracer Experiment, described in papers and reports by Hanna [14] and Policastro et al. [6,15]. Although Meroney's model did not include drift droplets evaporation, it successfully predicted plume rise and droplet deposition. Following the path opened by Meroney, Lucas et al. [16] replicated the problem of Chalk Point cooling tower including evaporation and studied the influence of psychrometric ambient conditions on the deposition. Referring to studies of mechanical draft cooling towers drift deposition in urban environments, Meroney [17] also faced this problem. He proposed a protocol to generate a typical set of coefficients that might be used to adjust the results of seasonal or annual deposition predictions using analytic programs such as ISCST3 or SACTI. However, he did not present experimental results to validate his results showing a lack of data in the literature. Consuegro et al. [18] reported a numerical model of the explosive Legionella's outbreak which took place in 2001 in Murcia, pointing out that CFD methods represent a suitable alternative for estimating cooling tower drift, droplet evaporation and deposition.

The experimental procedures reported in the literature relating to cooling tower emissions are presented in two lines of action primarily. The background flow fields and gaseous plume motions can be accurately predicted in environmental wind tunnels at moderate velocities. However, the correct scaling of droplet and particle drift requires the simulations to be run at extremely low facility velocities, which distorts the model flow fields [19–21]. A comparison between the results obtained through dispersion experiments in a wind tunnel and those obtained with the dispersion model AUSTAL2000 can be found in Bahmann and Schmonsees [22].

The second experimental approach is to carry out tests in full-scale facilities. Full-scale tests can be classified into those that study the evolution of the plume, those that study the amount of drift water and those that also measure the deposition. The behavior of cooling tower plumes has been studied among others by Huber and Snyder [23]. Many works relating to the measurement of the amount of drift water emitted by cooling towers can be found. A very detailed method comparison was carried out by Golay et al. [24]. They described numerous techniques and devices for measuring cooling tower drift emissions. The results indicated that no single device is superior to the alternatives over the entire range of cases tested. Methods performing best under low water loading conditions utilize sensitive surface techniques. Methods performing best under high water loading conditions include the isokinetic mass sampling and chemical balance techniques. Lucas et al. [25] studied the drift loss emissions from a cooling tower without drift eliminator and then fitted with six different drift eliminators. Ruiz et al. [26] used the sensitive paper method to measure the emissions of a cooling tower: drift and PM_{10}. As PM_{10} calculation requires both the amount of drift and the size and number of drop information, sensitive surface methods were suggested for measuring in real facilities.

In reference to the experimental study of deposition in cooling towers, there are few studies in the literature. Martin and Barber [27] collected droplets of water falling from natural draft cooling tower plants on water-sensitive papers around several power stations at various distances and in different weather conditions. The smallest diameter of the drops recorded is limited to 60 μm. The work of Policastro et al. [28] is a complete record of experimental studies of drift and deposition carried out in a natural draft cooling tower working as a heat dissipation of 2640 MW thermal power Chalk Point in Maryland. Another study, conducted by the same group of scientists and described by Laulainen [29], was developed in two 13-cell rectangular mechanical draft-cooling towers at the Pittsburgh power plant MW AC 720. He used sensitive papers to carry out the experiments. Pena [30] measured the drift deposition rate at short distances (170 and 250 m) from the natural draft cooling towers at the Keystone Power Plant (U.S.). He also used sensitive papers and focused the work toward measurements at short distances downwind of a cooling tower where the air flow is disturbed because of the presence of the tower. The literature review has highlighted the usefulness of conducting tests in a mechanical cooling tower of a single cell in an urban environment since no experimental data are available with these features.

The main objective of this study was the measurement of the amount of drift emitted and deposited from a mechanical draft cooling tower located in an urban environment. Secondary objectives were to develop a database that can be used in drift deposition models for mechanical draft cooling towers and to analyze the influence of ambient variables on downwind deposition. A methodology for the evaluation of drift emissions and deposition is proposed using a digital image process algorithm for the Sensitive Paper method. Measurements of environmental conditions were carried out simultaneously to complete the experimental information. Results include both drift and deposition in terms of droplet distribution and water mass flow. Experiments have been defined to study the effect of wind speed and direction on the deposition, showing results of four tests combining two predominant wind directions and two levels of wind speed.

2. Methodology

2.1. Experimental apparatus

A mechanical forced draft cooling tower placed at the roof of a two-floor building in an urban environment (Universidad Miguel Hernández in the city of Elche, southeast Spain, 38° 16′ 43.06″ N, 0° 41′ 26.80″ W) is employed to carry out the drift and drift deposition experimental tests. This cooling tower has a cross-sectional area of $0.7 \times 0.48\,m^2$, a packing section 1.13 m and a total height of 2.597 m. Nominal values for operating conditions are $1.44\,kg\,s^{-1}$ for the mass flow rate, 30 kW power and 5 °C of range (inlet and outlet water temperature difference). The fill consists of a honeycomb structure. The airflow rate is circulated counter-flow by an axial fan, which is maintained at 50 Hz by a frequency switcher. A complete description of the experimental facility can be found in Lucas et al. [25].

Regarding the operating conditions, a general-purpose data-acquisition system (HP 34970A) was set up to carry out the experimental tests. To measure the ambient conditions during the experiments, a 40 m tall meteorological tower located in front of the building is used. The meteorological tower is equipped with three wind anemometers, three wind vanes and three thermo hygrometers located at three different heights, 15, 25 and 40 m. Additionally, a barometric sensor is placed at the height of 10 m (same plane of the cooling tower). In this way instantaneous (up to 1 s) and averaged profiles of the abovementioned magnitudes during the test

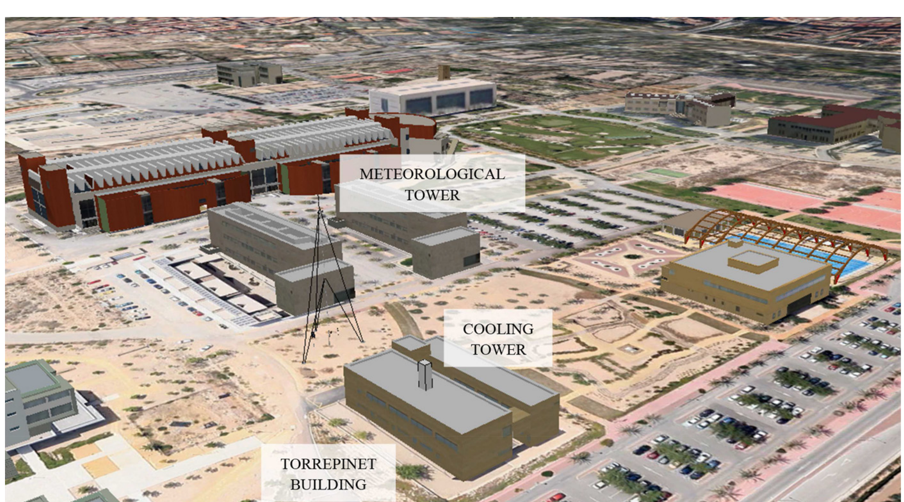


Fig. 1. 3D view of the reference cooling tower, located at the Miguel Hernández University, in southern Spain. Relative location between the Torrepinet building, cooling tower and meteorological tower.

Table 1
Cooling tower and meteorological tower measuring instrumentation specifications.

Parameter	Sensor	Measuring range	Precision
Cooling tower sensors, general specs			
Water temperature	RTD pt100	−200 to 600 °C	±0.08 °C
Water volume	Oval wheels	2–20 m^3 h^{-1}	0.4% depth scale
Exit air velocity	Vane anemometer	0.5–20 m s^{-1}	0.1 m s^{-1} ±1.5% reading
Ambient temperature	RTD pt100	−50 to 50 °C	±0.2 °C
Ambient humidity	Capacitive sensor	0–100%	±4% (0–10%) ±3% (10–90%) ±4% (90–100%)
Wind velocity	Cup anemometer	0–50 m s^{-1}	±0.3 m s^{-1}
Exit tower temperature	Capacitive sensor	−20 to 80 °C	±0.3 °C
Exit tower humidity	Capacitive sensor	0–100%	±2%
Meteorological tower sensors, general specs			
Wind velocity	Cup anemometer	0–50 m s^{-1}	±0.5 m s^{-1}
Wind direction	Wind vane	0–360 °	±5 °
Ambient temperature	Resistive sensor	−30 to 70 °C	±0.1 °C
Ambient humidity	Capacitive sensor	0–100 °C	±3% (0–90%) ±5% (90–100%)

can be obtained. The sensors used during the experiments (cooling and meteorological tower) and their specifications are shown in Table 1. The relative location of the building, cooling tower and meteorological tower can be seen in Fig. 1.

2.2. Sensitive paper method

Sensitive Paper (SP) techniques are based on the collection of droplets taken away from a cooling tower by the air flow and collected by inertial impact thereof on a sensitive surface placed perpendicular to the flow. This paper is chemically treated (soaked in a potassium ferricyanide [$K_3Fe(CN)_6$] solution, dried and dusted with ferrous ammonium sulfate [$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$] powder).

A droplet impinging on the paper produces a well-defined blue stain on the pale yellow background of the paper. The size and shape of the stains are related to the speed of impact as well as to the original diameter of the drop.

The method was first described by Wilber and Vercauteren [31]. The capability of the method to provide drop size distribution data as well as the number of drops exiting the tower, makes it suitable for drift measurements in low drift scenarios [24]. It is also an appropriate method for real world conditions measurements due to its portability. The calculation of the amount of drift emitted from a cooling tower using the SP method covers three main stages: carrying out the tests, image processing stage and drift calculation. Refer to Ruiz et al. [26] for a detailed description of the application of the method to drift tests in the same experimental facility where the tests described here were performed, and specially for the image processing description. At this stage, the sensitive papers are digitized in BMP format by means of a high resolution scanner. Afterwards, a software platform is implemented in order to collect the information from the papers. Drop-like stains are identified by means of an image process and classified by a J48 decision tree classifier, discerning which droplets have their origin in real drops and which not. The accuracy of the droplet area sizing of the SP methodology has been determined to be within ±1 pixel (5.291 μm pixel^{-1}) of the true droplet area. Then the diameter of the drops (d_d) which caused the stains (d_s) is calculated using the

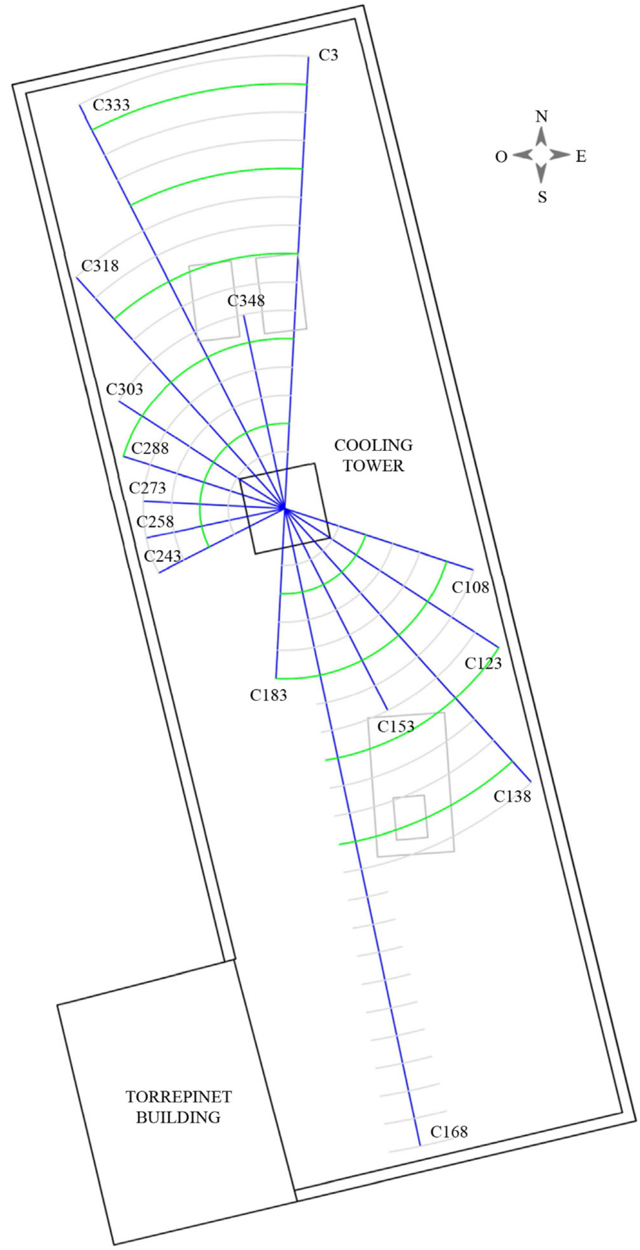


Fig. 2. Layout of the samples in cooling tower drift deposition study.

drop–stain relationship supplied by the manufacturer. Finally the amount of drift can be calculated according to the set of equations Eqs. (1)–(3), where the experimental impaction efficiency correction, ε, is considered (note that all the drops present in the airstream will not end up hitting the impactor). The latter is determined via the impaction velocity alongside the droplet diameter according to the experimental impaction curve for ribbons taken from the work of May and Clifford [32].

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

$$\dot{m}_s = \frac{A_T}{n_p} \sum_{j=1}^{n_p} \dot{m}_{d,j} \tag{2}$$

$$D = \frac{\dot{m}_s}{\dot{m}_w} \tag{3}$$

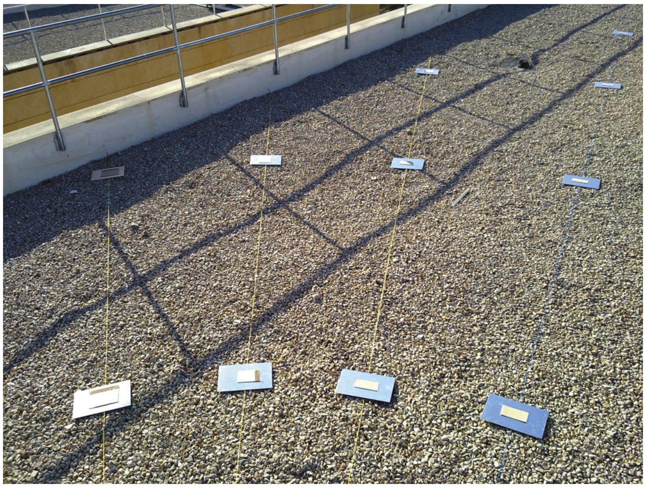


Fig. 3. Sensitive papers placed on the ground, covered and fixed to aluminium plates ready to be used in the deposition tests.

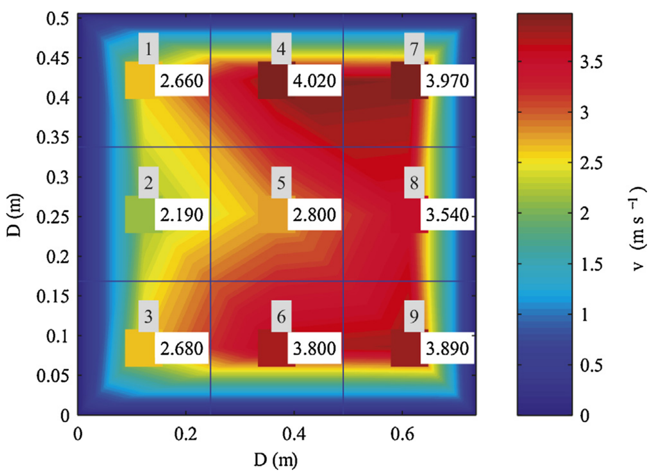


Fig. 4. Experimental velocity map for the experiment carried out on March 22, 2013.

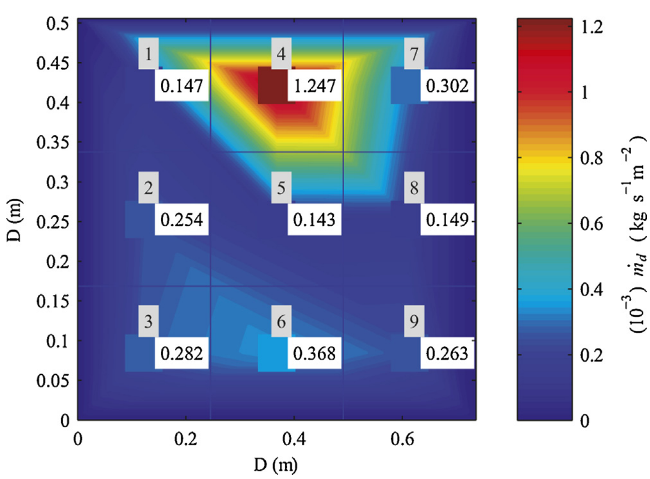


Fig. 5. Experimental drift results for the experiment carried out on March 22, 2013.

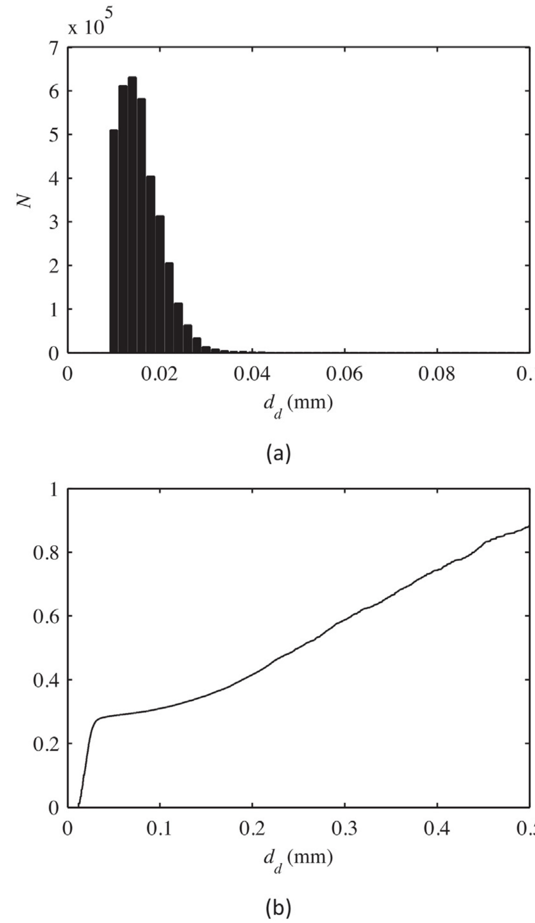


Fig. 6. (a) Histogram and (b) accumulated volume for the drift experiment carried out on March 22, 2013.

SP techniques are also suitable for drift deposition measurements, mainly due to their capability to provide drop size distribution data at ground level.

In downwind deposition measurements the analysis of the sensitive papers is more complicated compared to drift measurements because of the non-circular stains arising from the conditions met during this kind of experiments. As a result a great variety of stain shapes are encountered. Thus, the image process undertaken by the paper is adapted with regard to the abovementioned process Ruiz et al. [26] to calculate drop diameter. The deposition rates can be calculated for each paper placed on the ground (n_p^d) according to Eq. (4).

$$\dot{m}_{d,j} = \frac{\rho_w \pi}{6 A_p t_{\text{exp}}} \sum_{i=1}^{N} d_{d,i}^3 \tag{4}$$

2.3. Experimental procedure

The procedure for the experimental measurement of drift and downwind deposition in a cooling tower consists of distributing a set of sensitive papers (Teejet model hydrosensitive papers sized 76 mm × 52 mm, were used in the tests) in order to collect the droplets taken away from the cooling tower by the air flow (drift) and deposited on the ground (deposition). Ambient and operation conditions are measured by means of a data acquisition system and the meteorological tower during the experiments.

Before getting started, the monitoring of the meteorological conditions (wind direction and velocity) is required. As a consequence, forecast sources are used to select the most suitable moment to carry out the experiments in terms of the stability of wind direction and velocity and the ambient temperature. For each drift experiment, a velocity map of the cooling tower exit section of the tower is performed. The outlet area is divided into nine

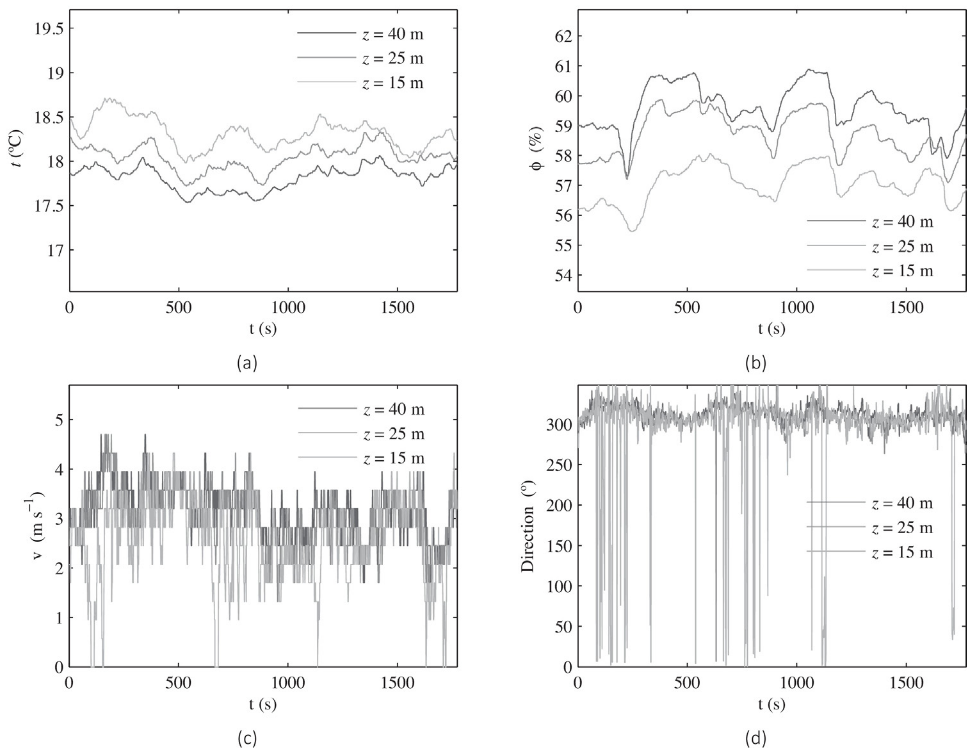


Fig. 7. Evolution of ambient conditions as a function of time and height during the deposition experiment carried out on March 22, 2013.

measurement areas (thus n_p is taken as equal to 9) from which the averaged air velocity at the exit of the tower is obtained.

Afterwards, the drift experiment is carried out following the methodology described in Ruiz et al. [26]. Sensitive papers are attached in three numerated PVC plates, placing three papers on each one so that the nine areas mentioned before are covered. The samples are maintained in a horizontal attitude by the plates. To establish the exposure time a trade-off solution will be adopted taking into account two conditions: obtaining the maximum number of stains without overlapping between drops and paper edges not becoming green due to the flow of moist air concentrated in that area. This time is inversely proportional to the number of drops per unit of time and surface. The papers exposure time is 3 s for drift experiments.

Regarding the downwind deposition tests, sensitive papers are set in a series of circular arcs. 15 cords are used for that purpose, covering the area without structural interferences that match the predominant wind directions (northwest (NW) and southeast (SE) zones, Fig. 2). Those directions should be sought for the planning of the experiments. These cords are set at equal angular spacings (15°) and are marked every meter distance, indicating possible placements for the sensitive papers. The code for identifying the position of the papers around the tower is established in terms of the angle from the north direction and the distance to the cooling tower. For example, paper "C3D6" is the paper placed at an angle of 3° from north and at 6 m distance from the tower while paper "C318D16" is located at the cord pointing almost towards NW and at 16 m distance from the center of the tower.

Sensitive papers are distributed covering an area of 90° maximum (θ=±45°, depending on the free available space and the researcher's judgment), centered on a principal cord which is the closest one to the predominant wind direction (θ = 0°). Along the process of droplet collection, sensitive papers are maintained in a horizontal attitude fixed to aluminium plates (302 mm × 201 mm).

Initially, papers are covered while set out until all of them are correctly distributed at ground level in the experimental area. Afterwards, they are uncovered at the beginning of the experiment. On average, the test runs are about 30 min duration, which has been found to be adequate to meet the analysis requirements. The area covered by the papers in deposition tests is larger than in drift tests and, therefore, the exposure time is much higher.

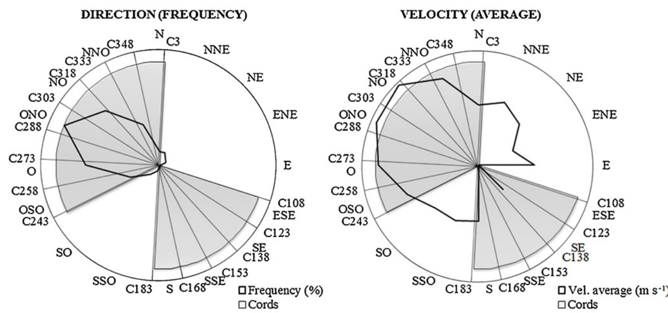
Fig. 3 shows the papers attached to the aluminium plates and placed at their corresponding positions on the cords selected for the deposition test.

3. Results and discussion

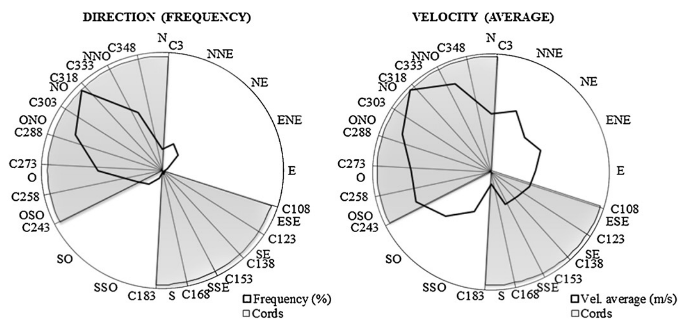
The results obtained from the four experiments presented in this paper, carried out at the experimental facility by means of the sensitive paper method, are described in this section. These cases have been selected among more than 20 tests conducted in the pilot plant because the characteristic psychrometric properties (ambient temperature, t, and relative humidity, ϕ) are similar between them. In this sense, the influence of wind velocity, v, and wind direction can be evaluated. Table 2 summarizes the cases main characteristics measured by the cooling tower sensors. For the purpose of comprehensively describing the cases, this section has been divided into three parts: test description, tests results and trends and discussion. In each one of them, drift results, characterization of ambient conditions using the meteorological tower and deposition results are presented separately.

Table 2
Summary table of the performed tests. t and ϕ are related to deposition tests and the cooling tower sensors.

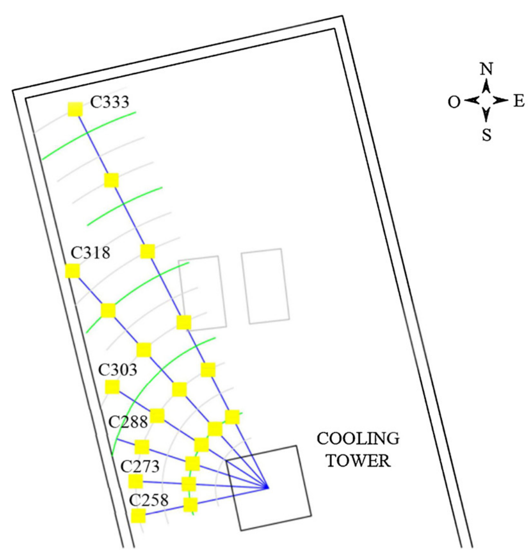
Test	Date	t (°C)	ϕ (%)	Direction	v (m s^{-1})
1	03/31/2014	19.24	36.82	SE (303.75–326.25°)	3.27
2	10/15/2012	18.19	38.45	NW (123.75–146.25°)	3.72
3	03/22/2013	18.81	58.49	SE (303.75–326.25°)	2.38
4	10/22/2012	18.38	60.14	NW (123.75–146.25°)	2.92



(a) Prior to the deposition experiment wind rose



(b) Deposition experiment wind rose



(c) Placement of the sensitive papers

Fig. 8. Wind roses (a) prior and (b) during the deposition experiment carried out on March 22, 2013. (c) Schematic arrangement of the placement of the sensitive papers on the roof of the building.

The results of both, drift and deposition tests, are presented in terms of emissions and the main characteristics of the drop distributions, whereas ambient conditions are characterized using correlations as a function of height.

3.1. Test description

This section presents the results obtained taking as an example the experiment carried out on March 22, 2013 (test 3, Table 2).

3.1.1. Drift results

The ambient conditions measured by the metereological tower sensor located at $z = 15$ m during the experimental drift test are, ambient temperature $t = 18.18\,^{\circ}$C, and ambient relative humidity, $\phi = 62.37\%$. As explained in Section 2.3, the air flow speed at the cooling tower exit is measured by dividing the surface into nine quadrants, where the sensitive papers were located. Fig. 4 depicts the velocity map obtained in the experiment. The grey squares represent the number of the paper whereas the white ones show the mean velocity of the exit flow at each of the nine subdivisions. The level of air velocity for points outside the nine paper locations, has been calculated by means of a linear interpolation. The non-uniformity of the exit velocities is related to the relative position between the distribution duct (central line, positions 2, 5 and 8) and the fan (located at south zone, positions 1, 2 and 3).

The results calculated for each sensitive paper located at the cooling tower exit surface are presented in terms of the escaped

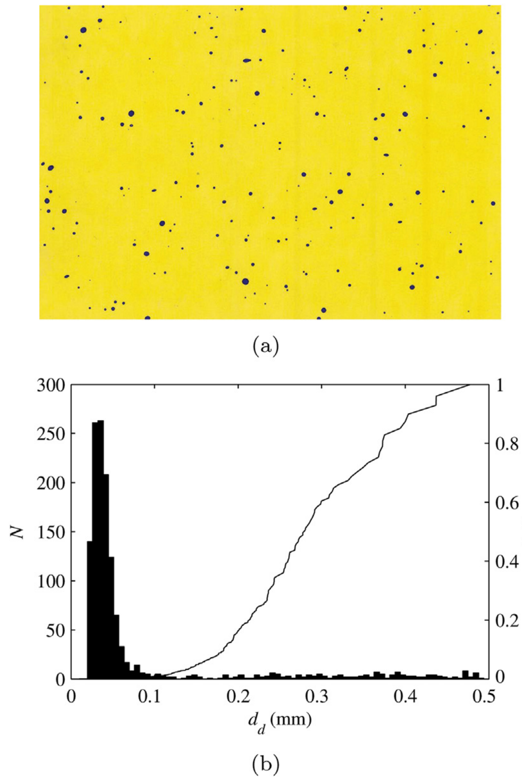


Fig. 9. (a) Sensitive paper and (b) histogram and accumulated curves for the deposition experiment carried out on March 22, 2013 (paper "C258D5").

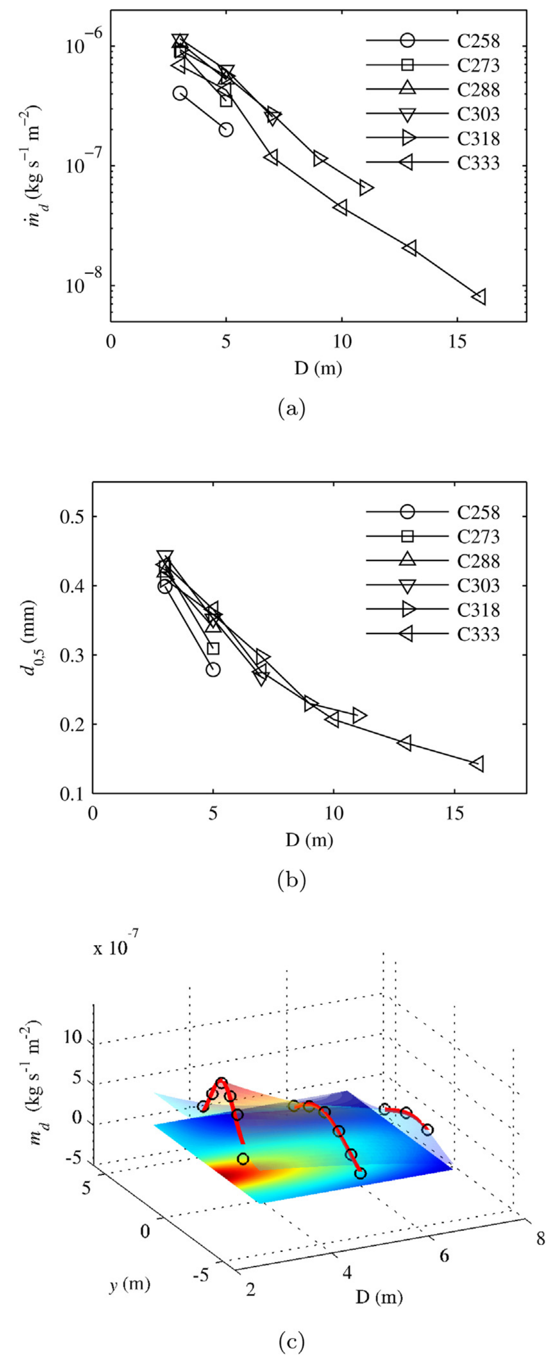


Fig. 10. (a) Levels of water deposited per unit of time and surface as a function of the distance from the tower in the deposition experiment carried out on March 22, 2013. (b) Variation of the characteristic diameter as a function of D. (c) Drift deposition colormap.

mass flow by unit of area, $\dot{m}_d$, the characteristic diameter, $d_{0,5}$ (which represents the drop diameter that causes 50% of the accumulated water volume) and the accumulated volume of water $\sum V$ (Table 3). It can be observed that the drift by unit of area and characteristic diameter are homogeneous in the tower exit section, except for position 4. In this case the $\dot{m}_d$ is four times higher and the $d_{0,5}$ is double those obtained for the other positions ($\dot{m}_d = 1.247 \cdot 10^{-3}$ kg s^{-1} m^{-2}, $d_{0,5}$ = 0.341 mm). This can only be justified by the non-uniformity of the water distributed over the fill by the distribution system and a small contribution of the asymmetry of the outlet velocities. Fig. 5 shows the experimental drift colormap. Here the cooling tower exit surface, divided into the nine subdivisions where the papers are located, is colored depending on the $\dot{m}_d$ value. The level of escaped mass flow by unit of area for points outside the nine paper locations, has been calculated the same way as the velocity map.

The values calculated for the amount of water taken away (absolute and percentage) from the cooling tower, are $\dot{m}_s = 1.305 \cdot 10^{-4}$ kg s^{-1} and D = 0.0090%. It is noticeable that this experiment accomplishes the main standards concerning drift emissions: Royal Decree RD 865/2003 [33] in Spain, which establishes a maximum drift of 0.05% of the circulating water in the system and Australian Standard AS 4180.1 [34] which aims for a 0.02%. Regarding the characteristic variables of the exit drop distribution, $d_{0,5}$ = 0.264 mm and $\sum V$ = 37.436 mm^3. Fig. 6 displays the histogram of the drop distribution and the percentage accumulated volume curve at the cooling tower exit. The histogram shows that the most frequent drop diameters are smaller than 0.025 mm and that most of the drop diameters measured are below 0.25 mm. The total accumulated volume with 3 s exposure time, gives a total of 12.47 mm^3 s^{-1}. This value is reached with drop diameters up to 0.75 mm. The shape of the accumulated curve, which presents a sudden change of tendency not usual in this kind of representation,

Table 3
Results obtained for each paper in the experiment carried out on March 22, 2013.

Paper	$\dot{m}_d \times 10^3$ (kg s^{-1} m^{-2})	$d_{0,5}$ (mm)	$\sum V$ (mm^3)
1	0.147	0.032	1.741
2	0.254	0.128	3.012
3	0.282	0.183	3.343
4	1.247	0.341	14.804
5	0.143	0.078	1.701
6	0.368	0.279	4.363
7	0.302	0.275	3.584
8	0.149	0.159	1.767
9	0.263	0.194	3.121

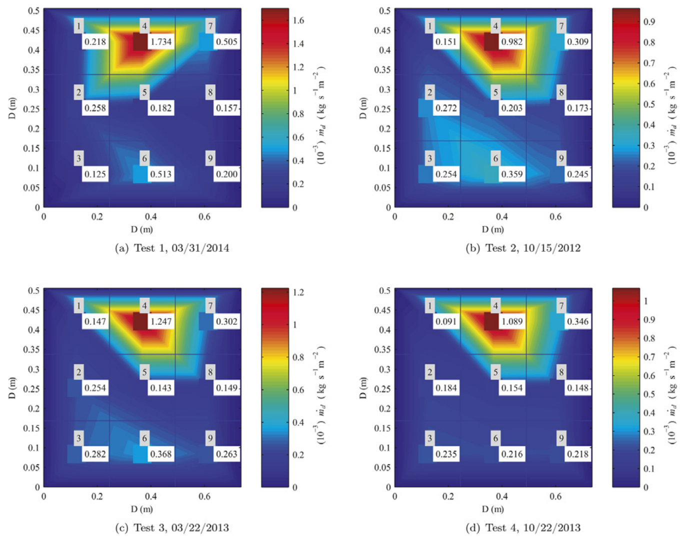


Fig. 11. Experimental drift results for the set of experiments carried out.

is presumably produced by two different mechanisms of generation. The first mechanism is related to the water droplets being torn out from the water film by the airstream. On the other hand, the other mechanism arises because of the thinning and breaking of the water film.

3.1.2. Ambient conditions

Fig. 7 depicts the temporal variation of the ambient conditions (temperature and relative humidity, wind velocity and wind direction) at different heights measured by the meteorological tower during the deposition test. Correlations of these profiles are obtained as a function of the height (z). Regarding mean wind velocity, the well known logarithmic boundary layer profile for wind velocity, $v(z)$, can be written as

$$v(z) = \frac{u_\tau}{\kappa} \ln\left(\frac{z}{z_0}\right) \tag{5}$$

Here u_τ is the friction velocity, κ is the von Kármán constant ($\kappa = 0.41$) and z_0 is the aerodynamic roughness height of terrain. Usually, Eq. (5) can be matched to the logarithmic boundary layer through the calculation of u_τ for a given value of v (typically for a height $z = 10$ m). Regarding ambient temperature, $t(z)$, and the ambient relative humidity, $\phi(z)$, linear profiles are assumed, Eqs. (6) and (7).

$$t(z) = t_{z=0} - \alpha z \tag{6}$$

$$\phi(z) = \phi_{z=0} + \beta z \tag{7}$$

As representative results for the test carried out on March 22, 2013, values fitting Eq. (5) are $u_\tau = 0.2356\ \mathrm{m\,s^{-1}}$, $z_0 = 0.1462$ m, whereas linear regressions provide $t_{z=0} = 18.586\,^\circ\mathrm{C}$, $\alpha = 0.01948\,^\circ\mathrm{C\,m^{-1}}$, $\phi_{z=0} = 55.781\%$ and $\beta = 0.09829\%\,\mathrm{m^{-1}}$, respectively, for ambient temperature and ambient relative humidity.

3.1.3. Deposition results

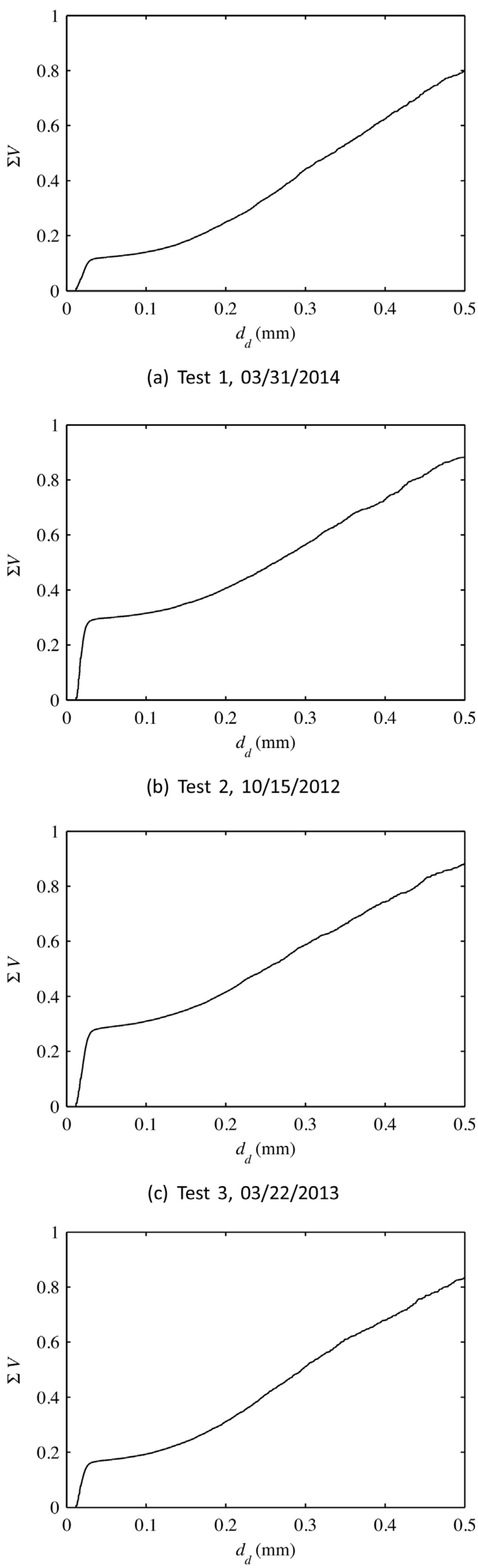
In deposition experiments, the placement of the sensitive papers on the ground is decided by measuring the predominant wind direction during the 10 min prior to the experiment. In this test example, the predominant wind direction is SE, Fig. 8(a), being the cord "C303" the closest to this direction. As a consequence, the placement of the sensitive papers is done as shown in Fig. 8(c), where "C303" is the central cord and three more cords have been added on each side. As a result, the seven selected cords encompass a test area of 90°. When the experiment is finished, the predominant wind direction during the experiment is checked. In this case, Fig. 8(b) shows that the predominant wind direction now points to the cord "C318" as the principal, with an averaged velocity in the interval 303.75–326.25° of 2.38 $\mathrm{m\,s^{-1}}$. Although the variation of the central cord is not usual, the unpredictability of ambient conditions makes it possible. The ambient conditions measured by the metereological tower sensor located at z = 15 m during the experimental deposition test slightly changed with respect to the drift experiment, being $t = 18.81\,^\circ$C and $\phi = 58.49\%$.

Deposition results are obtained by processing the papers. For each paper, individual curves (histograms and accumulated volume) are obtained. Fig. 9 shows, as an example, the sensitive paper and the individual curves calculated for the paper "C258D5". In the accumulated volume curve, Fig. 9 (b), the characteristic diameter is determined as the drop diameter that causes 50% of the accumulated water volume, $d_{0,5} = 0.2876$ mm in this case.

Fig. 10(a) represents the deposition level obtained at each cord and the distance to the tower. Each point corresponds to the individual results of a single paper, Fig. 9. As can be seen, in general, the $\dot{m}_d$ decreases as D is higher. The same pattern is observed for the $d_{0,5}$, as shown in Fig. 10(b). In this experiment, it is noticeable that the cord showing the highest level of deposition matches cord "C303". Depending on the shape of the wind rose during the experiment, the highest level of deposition cord can change with respect to the one closest to the predominant wind direction. Fig. 10(c) shows the experimental $\dot{m}_d$ results displayed by means of a colormap. This map shows the nearest area to the cooling tower colored by the $\dot{m}_d$ level. As in the velocity and escaped mass flow by unit of area maps, the middle values of the colormap (those outside the papers placed on the ground) have been obtained by means of a linear interpolation. Individual results of all the papers regarding the accumulated volume, percentage accumulated volume curves and histograms are not shown in this paper due to the amount of information. However, they can be found in the work of Ruiz [35].

3.2. Test results

In this section the results of the four experimental tests carried out at the pilot plant are presented, taking as a reference Section 3.1.



(a) Test 1, 03/31/2014

(b) Test 2, 10/15/2012

(c) Test 3, 03/22/2013

(d) Test 4, 10/22/2013

Fig. 12. Accumulated volume curves for the set of experiments carried out.

Table 4
Results obtained for the $d_{0.5}$, $\sum V$, $\dot{m}_s$, D, λ and σ for all the tests.

Test	$d_{0.5}$ (mm)	$\sum V$ (mm^3)	$\dot{m}_s \times 10^3$ (kg s^{-1})	D (%)	λ	σ
1	0.334	46.165	0.16101	0.01107	−1.4254	1.0359
2	0.263	34.975	0.12199	0.0084	−1.9978	1.3769
3	0.264	37.436	0.13053	0.0090	−1.9501	1.3241
4	0.295	31.808	0.11093	0.0077	−1.6320	1.1789

Fig. 11 depicts the $\dot{m}_d$ results for each paper located at the tower exit by means of a colormap. The first observation is related to $\dot{m}_d$ being homogeneous at the outlet section, except for position 4, where this value is multiplied by 4. It has been observed that in position 4, $d_{0.5}$ value is twice the average at the outlet section. These observations have already been described in Section 3.1.1. Concerning $\sum V$, the papers collect similar amounts of water in the four experiments.

The global results for drift experiments, both, in terms of emissions ($\dot{m}_s$ and D) and in terms of drop size distribution data ($d_{0.5}$ and $\sum V$), are displayed in Table 4. This table also includes the information regarding the fitting parameters for the log-normal distribution function (λ and σ). According to Ruiz et al. [26] this function is suitable for size distributions of aerosols and provides the best fits to experimental data in the range of cases studied. The main conclusion reached here is the evident repeatability of the results obtained. Note that tests have been selected with this purpose: similar t and ϕ. Mean value and standard deviation for drift results are, respectively, 0.00843% and 0.00054%. Hence, as expected, drift results are barely affected by wind speed and wind direction. Repeatability has not only been observed in the level of water emitted but in the shape of accumulated curves at the cooling tower exit surface, Fig. 12.

With regard to the characterization of ambient conditions, Table 5 presents the constants for the correlations for atmospheric variables as a function of height for the tests performed (Section 3.1.2).

Finally, and concerning downwind deposition results, attention is paid to the variation of the deposited water and characteristic diameter as a function of the distance to the tower for the different cords selected in each experiment, Figs. 13 and 14. Observed results show that both the amount of water deposited and the value of the characteristic diameter decrease with increasing distance from the tower. This observation has been confirmed for all the cords selected in the tests, not only limited to the highest deposition cord.

To quantify this fact, a general correlation which predicts $\dot{m}_d$ levels in downwind deposition tests as a function of D has been fitted to the experimental data. According to Schatzmann et al. [36], the typical ground measurement pattern as a function of y (distance perpendicular to distance D) obeys a Gaussian distribution. The difference between the predicted and the experimental results is less than 16% on average. The general form of this equation is shown in Eq. (8).

$$\dot{m}_d = (\mathcal{A}_1\, e^{\mathcal{A}_2\, \mathrm{D}})\exp -\frac{(y-(\mathcal{A}_3\,\mathrm{D}+\mathcal{A}_4))^2}{2\,(\mathcal{A}_5\,\mathrm{D}+\mathcal{A}_6)^2} \tag{8}$$

where constants $\mathcal{A}_1$–$\mathcal{A}_6$ for each test can be found in Table 6.

Table 5
Summary of constants for correlations of the ambient variables during the tests.

Test	u_τ (m s^{-1})	z_0 (m)	$t_{z=0}$ (°C)	α (°C m^{-1})	$\phi_{z=0}$ (%)	β (% m^{-1})
1	0.557	0.887	19.948	0.0449	22.688	0.0666
2	0.711	1.489	18.542	0.0233	35.913	0.0451
3	0.236	0.146	18.594	0.0195	55.782	0.0983
4	0.641	0.777	18.607	0.0121	55.160	0.0340

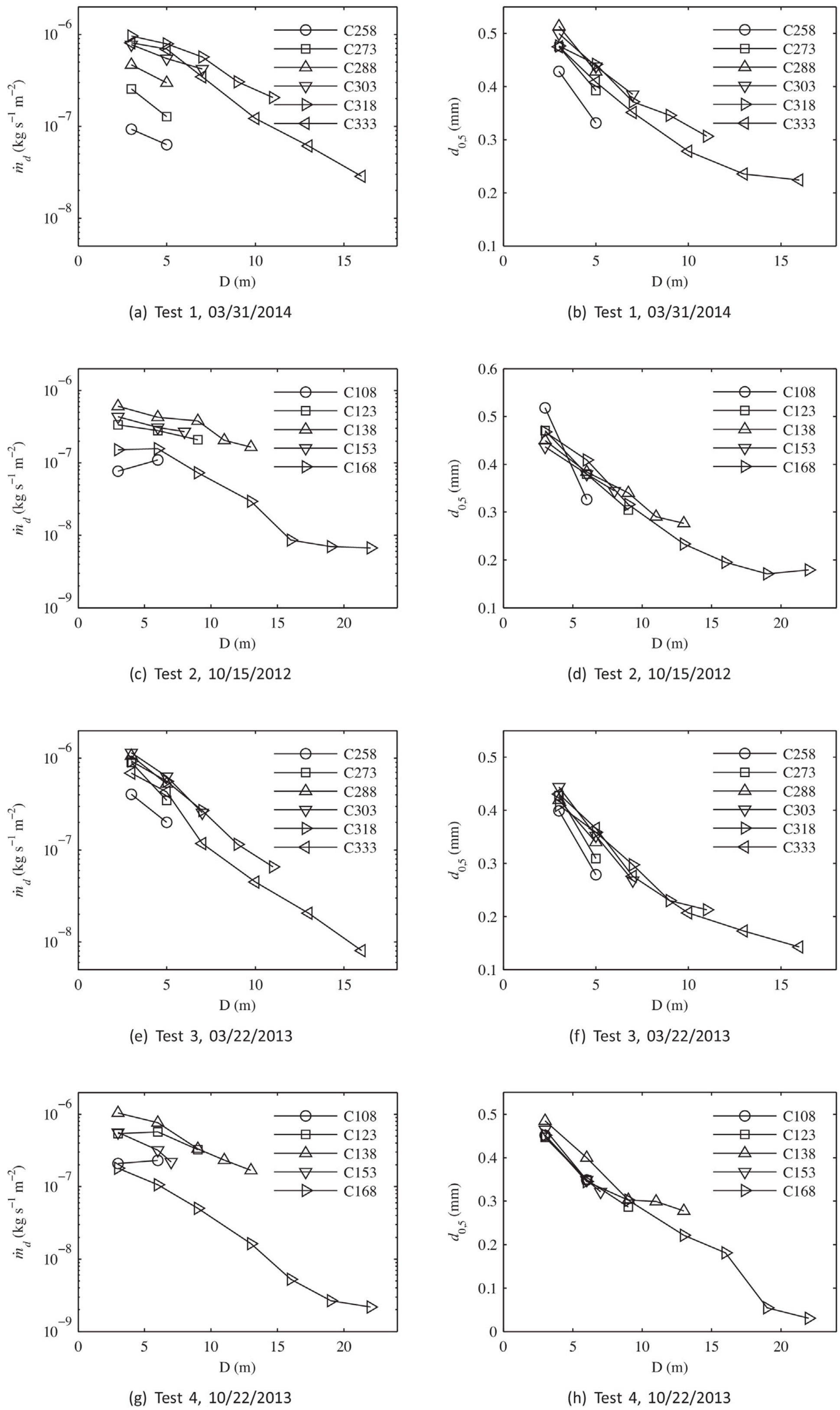
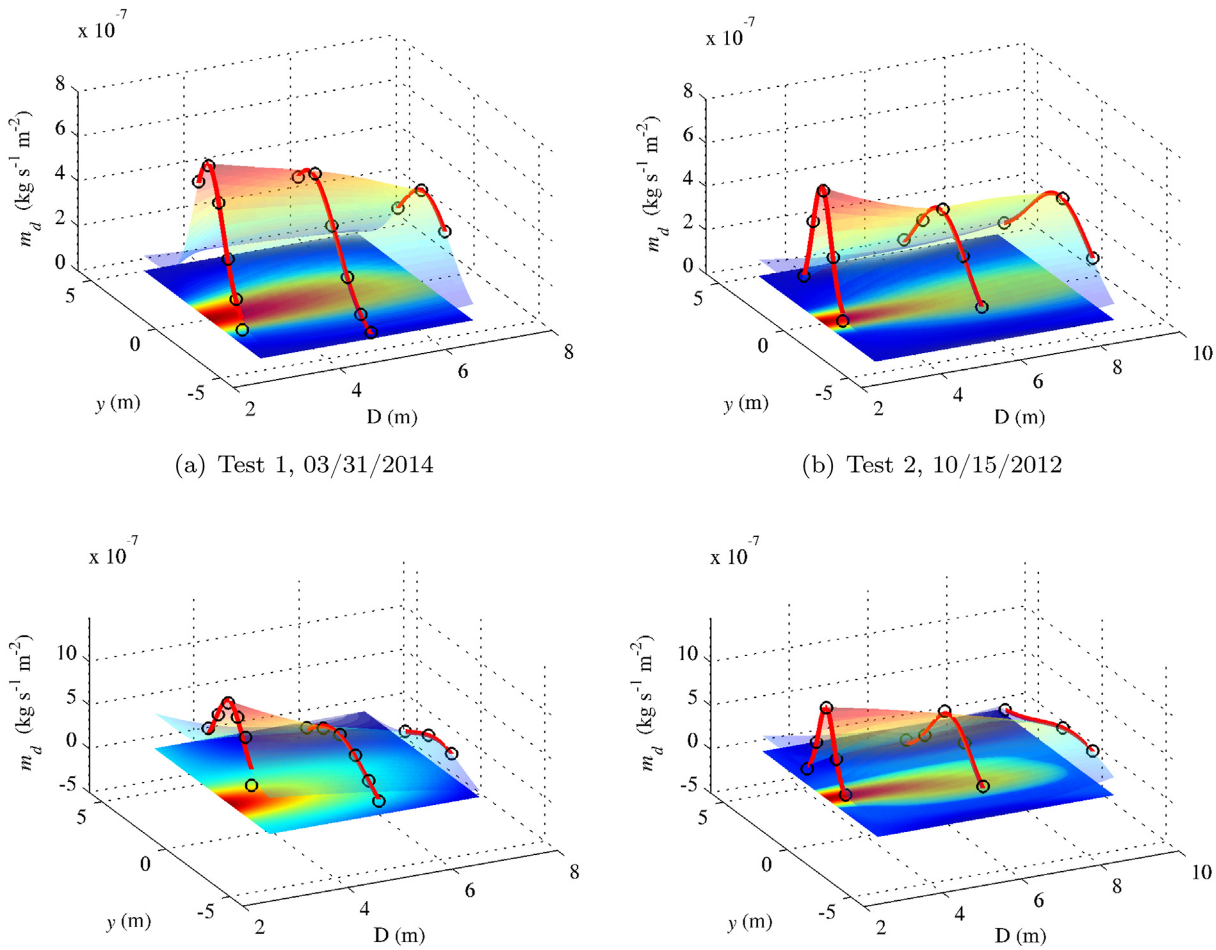


Fig. 13. Experimental drift deposition results for the set of experiments carried out.

3.3. Trends and discussion

The influence of the wind velocity and wind direction on cooling tower drift deposition is evaluated in this section. Regarding the wind velocity, Fig. 15 shows the comparison between experiments 1 and 3 (SE zone) as well as experiments 2 and 4 (NW zone) (Table 2). The amount of water deposited by area unit, $\dot{m}_d$ is depicted for the cord where the sum of all the papers gives the



(a) Test 1, 03/31/2014 (b) Test 2, 10/15/2012
(c) Test 3, 03/22/2013 (d) Test 4, 10/22/2013

Fig. 14. 3D experimental drift deposition results (colormap) for the set of experiments carried out.

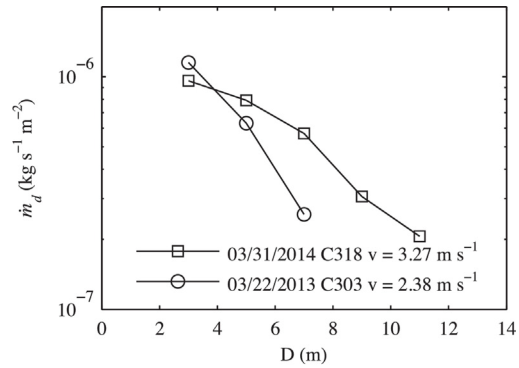
highest deposition (usually this cord is the same as the cord closest to the predominant wind direction during the experiment but obviously it depends on ambient conditions). This figure additionally includes the $d_{0,5}$ for each paper. The deposition level is always higher when having low wind conditions in positions close to the tower and this tendency changes for distances ranging 4–7 m, depending on the zone compared. The first behaviour is related to the lower drag force experienced by the water droplets, met in low wind conditions. Hence, the largest droplets tend to fall in the vicinity of the cooling tower. For higher wind speed level, the droplet distribution tends to be more homogenous, which leads to the second pattern observed (change of trend). In addition to the wind velocity level influence, the difference in wet bulb temperature may have a slight influence on the results. The wet bulb temperature is the driving force in the evaporation process. Since wet bulb temperature level slightly differs from tests 1 and 2 to tests 3 and 4, the above discussed trends can be also affected by this fact.

The comparison of the SE area is depicted in Fig. 15(a)–(b). For distances below 4 m, the deposition level is 20% higher in the area closest to the tower for low wind conditions. This trend changes from D > 5 m, and the downwind deposition levels converge at D ∼ 9 m, Fig. 10(a). The $d_{0,5}$ is higher for all the papers placed in the ground in high wind speed conditions.

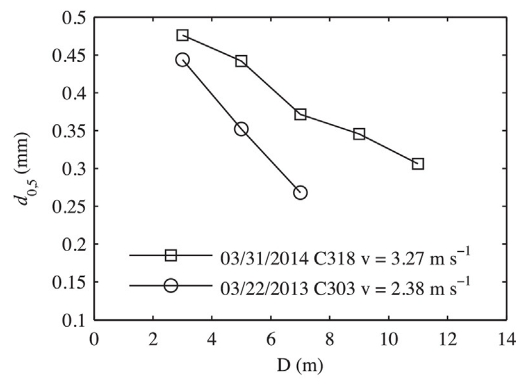
The comparison of the NW area, Fig. 15(c)–(d), provides similar observations than the SE comparison. Again, a higher deposition level is observed close to the tower with low wind conditions. In this case the difference is about 70%. Deposition levels merge at 8 m, and, from that position on, levels are similar in both experiments. This can be justified by the wind speed conditions: 0.5 m s^{-1} difference on average between high and low wind speed levels and the small difference in wet bulb temperature levels. This fact could also explain the difference in droplet distributions which is observed in the test zone comparison since the $d_{0,5}$ is higher for low wind conditions in almost all the papers.

Table 6
Constants for downwind deposition levels prediction.

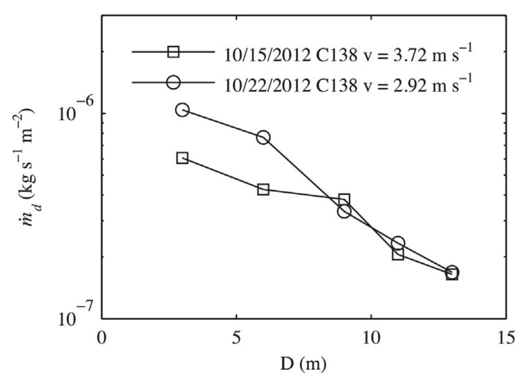
Test	$\mathcal{A}_1$	$\mathcal{A}_2$	$\mathcal{A}_3$	$\mathcal{A}_4$	$\mathcal{A}_5$	$\mathcal{A}_6$
1	$8.93963 \cdot 10^{-7}$	−0.107064	0.065025	0.37217	0.221439	0.621292
2	$6.33453 \cdot 10^{-7}$	−0.059303	0.020775	0.05026	0.273364	0.023143
3	$1.77558 \cdot 10^{-6}$	−0.243378	0.014890	−0.93013	0.223374	0.655403
4	$1.49723 \cdot 10^{-6}$	−0.147172	−0.177564	0.573486	0.369287	−0.554762



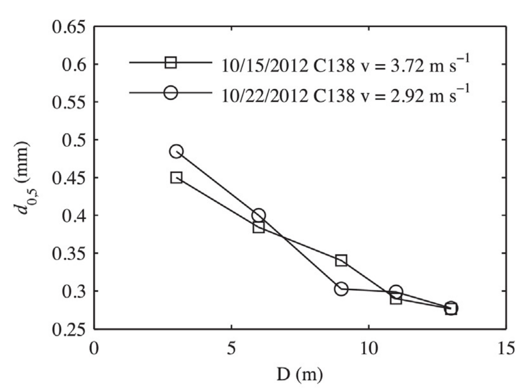
(a) $\dot{m}_d$ comparison, SE zone



(b) $d_{0,5}$ comparison, SE zone

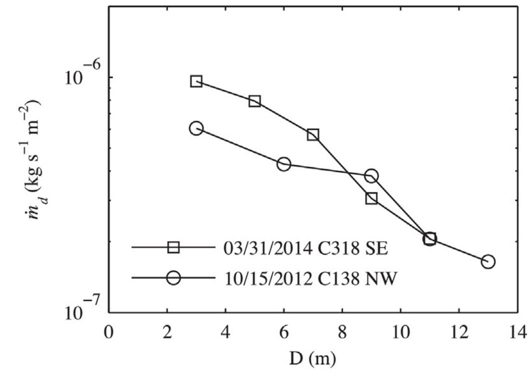


(c) $\dot{m}_d$ comparison, NW zone

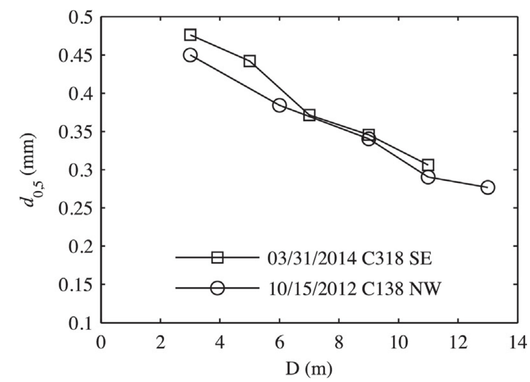


(d) $d_{0,5}$ comparison, NW zone

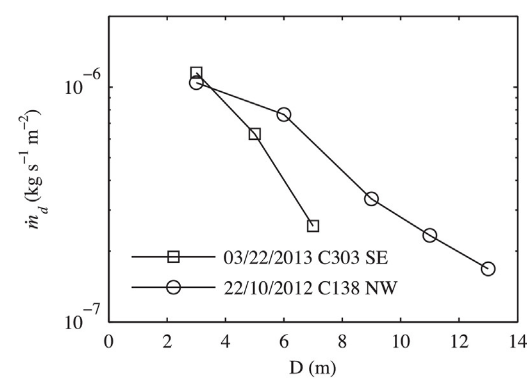
Fig. 15. Wind velocity comparison. Influence of velocity magnitude on downwind deposition and characteristic diameter.



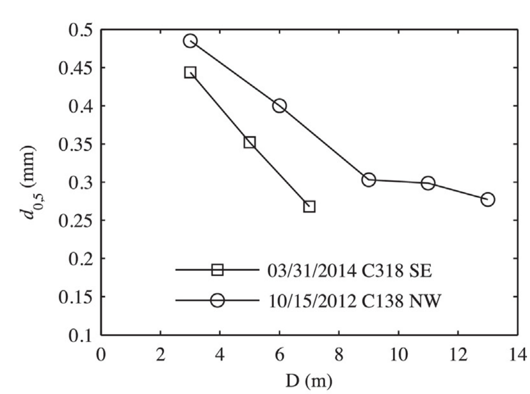
(a) $\dot{m}_d$ comparison, High wind



(b) $d_{0,5}$ comparison, High wind



(c) $\dot{m}_d$ comparison, Low wind



(d) $d_{0,5}$ comparison, Low wind

Fig. 16. Wind direction comparison. Influence of test zone on downwind deposition and characteristic diameter.

Concerning the wind direction influence, Fig. 16 shows the comparison between experiments 1 and 2 and between experiments 3 and 4. When comparing experiments 1 and 2 (Fig. 16(a)–(b), high wind speed level), it can be noticed that $\dot{m}_d$ is higher in the SE case. The difference observed can be up to 70% for distances ranging from 2 to 8 m. As a relevant result, the experimental area influences the $\dot{m}_d$ levels, since in both cases the wind velocity level is similar. This can be explained by the difference in the flow pattern enforced by the buildings in the surroundings of the tower (when the wind blows from SE direction it is affected by other buildings whereas in the other case the area is exempt, Fig. 1), the building itself and the asymmetry of air velocicities and drift rates at the cooling tower exit surface (see Figs. 4 and 5). The comparison between experiments 3 and 4 (Fig. 16(c)–(d), low wind–speed level), shows similar patterns. Close to the tower, a higher deposition level is observed when the wind blows from SE (20%). Concerning the $d_{0,5}$, it is higher for NW zone in low wind conditions and all the papers whereas in high wind conditions is quite similar in both zones. In this case the wet bulb temperature has no effect on the results since the compared cases share the same value of this magnitude.

The experimental trends regarding the variation of the level of deposited water as the distance to the cooling tower exit increases, agree with those available in the literature [13,29] for natural draft cooling towers. Additionally, some of the experimental results presented in this work have been used to validate the numerical model reported by Consuegro et al. [37]. All the predictions of the numerical model (influence of wind velocity and wind direction on cooling tower drift deposition and characteristic diameter) seem to be in agreement with the experimental test results.

4. Conclusions

In this paper, cooling tower drift and deposition emissions in an urban environment as well as the ambient conditions have been simultaneously measured in order to assess the cooling tower environmental impact. The lack of similar studies in the literature motivated this investigation. The field observations regarding the four experimental tests carried out using the sensitive paper method and under different environmental conditions can be summarized as follows:

The effect of wind speed and wind velocity was found negligible in drift emission experiments. In the case of the $\dot{m}_d$ level, it was observed that it was homogeneous at the cooling tower exit surface except for position 4, where this value was four times higher than in any other position. This fact was explained by the non-uniformity of the water distributed over the fill by the distribution system and a small contribution of the asymmetry of the outlet velocities. Percentage drift results were found to be below the Spanish and Australian standard limits (0.05% and 0.02%, respectively).

Regarding the deposition experiments, the experimental reduction observed for the $\dot{m}_d$ and the $d_{0,5}$ levels range from 72.9% to 92.9% and 38.4–78.7%, respectively, for the main cord and $0 \le D \le 13$ m.

The influence of ambient conditions on cooling tower drift deposition was analysed by comparing the tests according to the wind velocity and wind direction. With reference to the comparisons in which the wind velocity is analyzed, results showed that close to the tower ($D < 3$ m) there was a higher deposition level (20–70% higher, depending on the compared zone) for the experiment with low values of wind velocity. The shift of trend of the deposition level occur roughly for 4–7 m, and it seemed to be related to the level of the wind velocity and wet bulb temperature of the experiments compared.

Concerning the wind direction, a higher deposition level was observed when the wind blew from SE (45% higher on average). The difference was related to the velocity of the experiment (averaged velocities of 3.5 m s^{-1} and 2.65 m s^{-1}). This fact could be justified either by the arrangement of buildings in the surroundings of the tower (even the building itself) or by the asymmetry of the water emitted in the exit tower section.

Finally, it is worth noting that these measurements would allow us to establish a database for use in drift deposition model validation. The usefulness of having a validated numerical model for use in cooling tower drift deposition evaluation relies on the capacity of detecting potential sources of legionella spreading and evaluating the affected area by a cooling tower.

Acknowledgements

The authors acknowledge the financial support received from the Spanish Government, through Projects ENE2013-48696-C2-1-R and C2-2-R, by the FEDER (Fondo Europeo de Desarrollo Regional) as well as by the Séneca–Agency for Science and Technology of the Region of Murcia, Spain (Project 15184/PI/10).

Appendix A. Supplementary Data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.enbuild.2016.04.076.

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