A MODIFIED PARTICLE TRACKING VELOCIMETRY TECHNIQUE TO CHARACTERIZE SPRINKLER IRRIGATION DROPS

By

Félix-Félix J.R.^{1*}, Salinas-Tapia H.², Bautista-Capetillo C.³,

García-Aragón J.², Burguete J.⁴ and Playán E.⁴

Abstract

Numerous methodologies have been developed to characterize sprinkler irrigation drops with the purpose of improving irrigation efficiency and controlling soil erosion and compaction. This paper presents the laboratory characterization of the morphology and velocity of drops in their free-falling trajectory as influenced by drop diameter and wind speed. For this purpose, a Particle Tracking Velocimetry technique with in-line volumetric illumination was implemented. Hypodermic needles were used to produce droplets of uniform size. Two needle diameters resulted in drops with average diameters of 1.94 and 2.94 mm. Drops were illuminated with a double-pulsed laser beam or a LED lamp. Drop characterization reached an elevation of 4.28 m and occasionally attained terminal velocity. Motion blur was suppressed using a deconvolution filter. Drop equivalent diameter, velocity, chord ratio, canting angle and trajectory angle were determined using an *ad-hoc* software. The experimental approach led to the measurement of real drop size by illuminating a volume in the capture zone; Drop shape ranged from quasi-sphere to

¹Doctoral student, Centro Interamericano de Recursos del Agua, Universidad Autónoma del Estado de México, Carr. Toluca-Ixtlahuaca km. 14.5 San Cayetano de Morelos, Toluca Estado de México.

²Professor, Inter-American Water Resources Center, Universidad Autónoma del Estado de México, Carr. Toluca-Ixtlahuaca km. 14.5 San Cayetano de Morelos, Toluca Estado de México.

³Professor, Maestría en Ingeniería Aplicada Orientación Recursos Hidráulicos, Universidad Autónoma de Zacatecas. Avda. Ramón López Velarde, 801. Zacatecas, Zacatecas, México.

⁴Researcher, Department Soil and Water, Estación Experimental de Aula Dei (EEAD) CSIC., Av., Montañana 1005, 50059 Zaragoza, Spain.

*Corresponding author: ramiroflf@gmail.com

ellipsoid. Drop deformation was more intense under high wind speeds. Ballistic simulations of drop fall were performed using sphere and ellipsoid drag force models. Both models resulted in excellent agreement with measured drop velocity, with the ellipsoid model performing marginally better. The robustness of the experimental equipment, particularly in combination with the developed LED lamp, announces future outdoor applications in real sprinkler irrigated fields. Such applications will provide insight on the governing processes, and data sets for the improvement of sprinkler simulation models.

Keywords: PTV technique, drop shape, drop dynamics, drag force.

Introduction

The analysis of moving water drops in the air requires experimentation to characterize their geometric and kinematic parameters and to develop and validate analytical approaches. There are clear differences in the formation, size distribution, and movement of water droplets emitted by sprinkler irrigation systems compared with natural rainfall water droplets. In sprinkler irrigation, a water jet breaks into drops as it is sprayed through a nozzle at a small vertical angle, whereas natural rain is usually generated in high altitude clouds and falls mostly perpendicular to the surface of the earth at terminal velocity (Ge et al. 2016).

When water drops are originated in sprinkler irrigation systems, their characterization permits to assess and limit their potential negative effects on the soil surface (erosion or mechanical compaction). Additionally, the analysis of water droplets can lead to the optimization of irrigation performance indicators, such as uniformity and efficiency, under different environmental, operational, and hardware conditions (Keller and Bliesner 1990; Bautista-Capetillo et al. 2012; Salinas-Tapia et al. 2014). The assessment of sprinkler irrigation systems requires this type of analyses to understand the processes and to conserve water, soil and energy. During the process of jet disintegration, drops are formed at different distances from the nozzle. These drops travel in the air subjected to their initial velocity, the action of gravity, wind speed and the resistance of the air to drop movement. When large, fast-moving drops impact the soil surface, a reduction in water infiltration rate has been observed due to a change in the physical properties of the soil surface, potentially causing crusting, runoff and erosion (King and Bjorneberg 2012). A number of researchers have found strong relations between these phenomena and the kinetic energy of large water drops (Thompson and James 1985; Kincaid 1996; Basahi et al. 1998; Bautista-Capetillo et al. 2012, Ge et al. 2016).

Drop characterization is a key activity to characterize natural precipitation, sprinkler irrigation systems (Li et al. 2015; Sudheer and Panda 2000; Playán et al. 2006) and other non-agricultural sprinkler applications, such as indoor fire protection (Wu et al. 2007). A number of methodologies have been applied to the characterization of water drops in sprinkler irrigation and natural precipitation. In order to compare the merits of each technique, these have recently been categorized as manual and automated techniques. Manual drop measurement methods include the stain method (Lowe 1892; Magarvey 1956), the flour pellet method (Laws and Parsons 1943; Kohl 1974; Li et al. 1994; Arnaez et al. 2007), the oil Immersion method (Eigel and Moore 1983; Cruvinel et al. 1999; Blanquies et al. 2003) and the photographic method (Sudheer and Panda 2000; Salvador et al. 2009; Abudi et al. 2012). These techniques have been successfully used in studies involving drop size measurements. However, most of these techniques cannot provide terminal velocity data, are punctual, are time consuming, and are less effective in wind conditions (Kathiravelu et al. 2016).

The characterization of isolated drops has recently been achieved using low-speed photographic techniques (Bautista-Capetillo et al. 2009; Salvador et al. 2009). The technique has the advantage of being physically based. Critical disadvantages include the following: (a) The number of images should be large, since a considerable percentage of images are discarded due to lack of reliable information; the decision to include or remove an image depends on the criterion of the analyst; (b) the drop variables required to estimate diameter, velocity and angle are manually measured, causing perception errors; and (c) the characterization of one drop requires between 4 and 7 min.

On the other hand, thanks to the recent development of high-speed cameras and sophisticated lighting equipment (laser), non-invasive techniques have been developed. This is the case of optical disdrometers (Hauser et al. 1984; Montero et al. 2003; Burguete et al. 2007; King et al. 2010),

and more recently optical imaging (Beard et al. 2010; Müller et al. 2013; Liu et al. 2014; Chowdhury et al. 2015). Some of these methods use high-speed cameras that allow measuring the velocity, diameter, and shape of the water drops while passing through a light sheet (laser beam).

Recently, Bautista-Capetillo et al. (2014) conducted 2D PTV (Particle Tracking Velocimetry) experiments to estimate the frequency of drop diameter and drop fall angle in a set of drops moving in the air, as well as to build drop velocity fields. An important advantage of this technique is the capacity to identify smaller drops ($d < 0.27$ mm) than the low-speed photographic method proposed by Salvador et al. (2009), the digital technique described by Sudheer and Panda (2000) or the optical disdrometer used by Montero et al. (2003). In these three techniques, the minimum measurable diameter was about 0.4 mm. Nevertheless, some difficulties were reported by Bautista-Capetillo et al. (2014) in their experimental procedure: sprinkler drops were photographed over a region illuminated with a laser light sheet adjusted to 3 mm in thickness. However, sprinkler irrigation generates scattered drops in a three-dimensional field. As a consequence, the diffraction of the light beam at the drop centroid could not be ensured. The determination of the real drop diameter was therefore not guaranteed.

In parallel, flow analysis has shown significant progress with the development of noninvasive semiautomatic techniques to evaluate flow properties through computational visualization methodologies. This is the case of Particle Tracking Velocimetry (PTV) for two-dimensional flow analysis, as well as Stereoscopic Particle Image Velocimetry technique (Stereo-PIV) and digital holography for three-dimensional flow (Adrian 1991; Jensen 2004; Salinas-Tapia et al. 2006). These techniques provide highly efficient tools for characterizing quasi-spherical particles, analyzing its distribution velocity, temperature, pressure, stress-strain, vibration, turbulence and vorticity in flows of different nature (Van Dyke 1982; Smits and Lim 2000).

New experimental approaches for the study of drop deformation during free fall have profited from the development of automated techniques. Raindrops tend to flatten out at the base with increasing size, fall velocity and drag force. Consequently, drops frequently develop the shape of an ellipsoid (Beard et al. 2010; Kathiravelu et al. 2016). Chowdhury et al. (2015) investigated drop morphodynamics through laboratory simulations of natural rainfall. Using high-speed imaging, these authors studied water drop sizes of 2.6, 3.7, and 5.1 mm to measure their velocity and shape parameters. Among them, the ratio of the maximum vertical and horizontal drop chords, the canting angle and the relative fluctuation of chords. They identified three distinct drop fall zones: in the first zone, drop shape adjusts to source-induced oscillations; in the second, drop shape equilibrates to achieve terminal velocity; and the third zone, equilibrium-shaped drops fall at terminal velocity. Beard et al. (2010) reported on the equilibrium shape of drops, and on how this shape continuously evolves from a quasi-sphere to a flattened shape and back to the quasi-sphere. Additionally, the oscillation sequence of large drops was described, ranging from axisymmetric to transverse.

From the point of view of meteorological applications, morphodynamic properties of raindrops such as terminal velocity, shape, oscillation and internal circulation have been widely studied. A key goal of such studies has been to develop and evaluate precipitation simulation models (Muller et al. 2013; Beard et al. 2010; Chowdhury et al. 2015). In contrast, the study of these properties in sprinkler irrigation drops has been limited. A detailed characterization of drop geometry and dynamics will lead to improvements in the predictive capacity of sprinkler irrigation simulation models. Ballistic theory constitutes the most common approach when it comes to simulating the trajectory of sprinkler water droplets (Fukui et al. 1980; Li and Kawano 1995; Vories et al. 1987; Carrión et al. 2001). According to this theory, a sprinkler emits spherical

droplets of different diameters. Drop trajectory is influenced by its initial velocity, the gravitational force, the wind and the drag force (Vories et al. 1987; Carrión et al. 2001; Dechmi 2002; Playan et al. 2006). The classical drag model presented by Okamura (1968) was developed for spherical drops. However, sprinkler drops are subjected to relevant deformations along its trajectory, just like raindrops. In addition, the aerodynamic force acting on the drop is primarily determined by its shape (Müller et al. 2013). This justifies the need for further understanding of drop deformation. Recently, Paniagua (2015) presented a drag model specifically designed for deformed drops.

This research presents the characterization of the size, morphology and velocity of water drops of different diameters precipitated at different wind speeds, under controlled conditions, implementing an optical Particle Tracking Velocimetry (PTV) technique with in-line volumetric illumination. Specific objectives include: 1) to evaluate a new experimental approach (PTV) proposed to minimize the measurement errors in sprinkler irrigation drop characterization reported in previous efforts; 2) to adjust the image processing algorithm PTV developed by Salinas-Tapia et al. (2006) for this application; 3) to apply robust, low-cost alternative illumination techniques; 4) to investigate in laboratory conditions reproducing sprinkler irrigation drop morphology and dynamics; and 5) to assess the drag force model presented by Paniagua (2015), specifically designed for deformed drops.

Materials and methods

This research was carried out at the laboratory of flow visualization, *Inter-American Water Resources Center* (CIRA), Toluca, México. Different experimental aspects were considered during the planning of this research, which were implemented in four different experiments.

Experimental aspects

Drop production

Hypodermic needles with internal diameter of 0.23 and 0.80 mm were used to produce small and large drops, respectively. The needles were inserted through holes drilled at the bottom of a plastic container, which had a diameter of 0.12 m and a height of 0.20 m. The device was closed and sealed with a lid connected to a constant head water supply. Upon their separation from the needle, drops experimented free fall, and were characterized at one or several points along their downwards trajectory.

PTV system

The PTV system used in-line volumetric illumination, and was composed by various elements. The main ones were: 1) an illumination system; 2) a high-speed CCD camera manufactured by Pulnix Jai (Japan). The camera had a temporal resolution of 250 frames per second and a spatial resolution of 1024 by 1040 pixels (the CCD pixel size was 7.4 microns), and was equipped with a 50 mm lens manufactured by Nikon (Japan); 3) a series of optical accessories (mirrors and lenses); 4) a synchronizer NI (trigger) to control the image acquisition sequence and the light; and 5) the PTV SED v2.1 software for image processing, developed by Salinas-Tapia et al. (2006), which was modified and applied in this study to obtain the diameter, velocity, angle and morphological parameters of water drops in the different experimental conditions. According to previous

studies reporting on the PTV technique, tracers are required to visualize the fluid behavior. Due to the nature of this study, water drops acted as tracers that diffracted light, which was captured by the CCD sensor. Consequently, tests were performed in complete darkness, and the capture zone was illuminated. This setup permitted to obtain images containing perceptible information for digital processing. Two experimental setups were used in this work, differing in the light source (Figure 1).

Illumination

The first illumination setup was based on a 15 mJ double-pulsed laser (with an exposure time of each light pulse of 0.4 microseconds) type Nd:YAG, manufactured by New Wave (Fremont, USA). In a traditional optical PTV system, the sheet formed by the laser light and the optical accessories is very thin (about 1mm), causing problems in the measurement of drop diameters larger than the thickness of the light sheet. Errors can also be generated if the light beam does not diffract the drop centroid (Figure 2c). In fact, the beam can illuminate a drop area not including the central drop axis, resulting in unreal measured diameters (Figure 2a and 2b). Controlling these PTV errors would require adjustments in the illumination and specific image capturing approaches.

In order to obtain correct measurements of drop size in all cases, a modification was made to the traditional PTV experimental setup. The light beam was horizontally directed towards the viewing area using mirrors. Once the beam was in the capture zone, it was amplified and collimated using an arrangement of two 100 mm focal length spherical lenses. This allowed to generate a plane wavefront and illuminate a larger volume than the capture zone instead of a plane of light, thus guaranteeing the capture of full-size particles. Figure 1a schematically presents the experimental setup using laser light.

On the other hand, installing the optical equipment requires high precision to direct and align the laser light to the capture zone. Additionally, this process consumes considerable time, depending on the user's skills to handle lenses, filters and mirrors. Moreover, the difficulty increases when the PTV technique is applied at different observation points, as it happens in the phenomenon of study, where the displacement of the optical equipment was necessary. Finally, the laser light equipment is best used in controlled indoor conditions, not being suited for the outdoor conditions that characterize sprinkler irrigation.

In an attempt to overcome these difficulties, a double-pulsed lamp composed of an array of high-power LEDs was developed. Each LED had a power of 3 W, with a wavelength in a range of 490-590 nm (the same wavelength as the laser light) and therefore green color. The goal was to ease and accelerate the experimental characterization of drops in different observation points under the same principle of volumetric lighting. The goal was attained since this simple device can be easily displaced in the laboratory. The LED lamp is controlled by a synchronizer to emit two consecutive light pulses (with milliseconds delay) during the exposure time of the camera. Additional features of interest of the LED lamp are its low cost and its potential adequate performance in the outdoor conditions typical of sprinkler irrigation. Figure 1b shows the experimental scheme used with the LED lighting.

An important trait of the LEDs regarding their use in conjunction with the PTV technique is the response time (the time that the LED takes to reach its maximum intensity of radiated light until its extinction). This parameter determines the frequency of image recording. The response time must be very low to prevent images from showing motion blur, particularly when analyzing phenomena involving high-speed particles. The LED used in this work had a minimum response time of 0.1 ms, allowing detection of droplets with velocities greater than 6 m s^{-1} .

Wind generation

Regarding the wind generator, a commercial cyclone fan (Model 3510, manufactured by Lasko, Hayward, U.S.A.) with three power levels (low, medium and high) was used. Wind speed was measured at different horizontal distances from the fan (0.20 to 3.50 m) using an automatic anemometer (Model 6410, manufactured by Davis, Hayward, U.S.A.) equipped with previously calibrated wind speed and direction sensors.

Wind speed (Ws , $m\ s^{-1}$) was measured at different distances from the fan to characterize the device and to assess if it could realistically simulate the wind conditions present in irrigated fields. Figure 3 illustrates the relationship between distance from the fan and wind speed, determined using the three fan operation levels. A wind speed range was identified between 1.45 and 8.74 $m\ s^{-1}$. Velocities of 1.84, 2.94, 4.54, and 6.95 $m\ s^{-1}$ were selected according to recommendations in irrigation design manuals, which suggest to operate sprinkler systems in areas where wind speed is lower than 5.5 $m\ s^{-1}$ (Peña, 2007). A no-wind condition was also used in the experiments. In order to verify the representativeness of the wind velocities measured with the anemometer, and to analyze the air flow distribution in a two-dimensional field, a Particle Image Velocimetry (PIV) technique (Adrian, 1999) was implemented. In this case, water vapor was used as tracer particles. An average of 100 pairs of one-pulsed images were captured instantaneously, establishing a separation time between pulses of light of one millisecond. Subsequently, images were processed using the adaptive correlation technique with the proVision-XS® v3.11 software. PIV permitted to estimate the velocity of water vapor particles on the drop analysis zone, and from this, the wind speed in its vertical and horizontal components.

Two experimental scenarios were analyzed: the fan was placed at two and three meters from the capture zone and operated at the low power level (level 1). Figure 4 depicts the cross-sectional air

velocity fields and contour maps of the average wind speed distribution, resulting from the application of the PIV technique to the 100 pairs of snapshots. In the figure, moderate spatial variability in W_s can be appreciated. The air flow lines permit to state that wind speed was quite uniform in the study area. Average wind speed modules of 1.15 m s^{-1} (Figure 4a) and 1.90 m s^{-1} (Figure 4b) were obtained at distances of 3 and 2 m from the fan, respectively. In both cases, the average of the vertical velocity component was less than 0.10 m s^{-1} . The horizontal component of the vector presented averages of 1.17 and 1.89 m s^{-1} at distances from the fan of 3 and 2 m, respectively, with coefficients of variation lower than 5%.

Experiments

A total of four experiments were performed, differing in some of the abovementioned aspects:

- Drop size: experiments were performed with Large and Small drops. Accordingly, the first character of the experiment name is L or S.
- Illumination: experiments were performed with lAser and lEd illumination. Accordingly, the second character of the experiment name is A or E.
- Wind conditions: experiments were performed under Calm or Wind conditions. Accordingly, the third character of the experiment name is C or W.
- Number of drop measurement points: experiments were performed using one or several drop measurement points along the drop trajectory. Accordingly, the fourth character of the experiment name is the number of measurement points (1, 4 or 9).

Consequently, the four experiments were named LAC1, LAW1, LEC4 and SEC9. Table 1 presents their characteristics regarding the elevation of the drop measurement points and the wind speed. Taking into consideration the four experiments, the different elevations and wind speeds, a total of 18 sets of drops were monitored. This led to the characterization of 1,115 drops obtained from

double-pulsed images, with an average of 62 drops per set. In a clear precedent to this paper, Bautista-Capetillo et al. (2014) processed 3,782 focused drops. These authors discarded drops whose diameter difference between pulse 1 and pulse 2 exceeded 20%, discarding 50% of their data. In this paper it was not necessary to apply this filter, since the capture zone was volumetrically illuminated using a plane wavefront, thereby obtaining all drops in full size. The difference in drop diameter between pulses 1 and 2 was always lower than 6%. A small percentage of drops (about 2%) were discarded for showing overlapping drops. This percentage could increase if phenomena with large dispersion and concentration of particles were studied. This could be the case of solid-set sprinkler irrigation, with a high drop density and a variety of drop trajectories. In this sense, the implementation of particle separation and reconstruction algorithms is recommended in future research in order to improve the proposed technique (Choo and Kang, 2004; Zhang et al. 2012).

LAC1 and LAW1 were designed to produce large drops (an average of 2.94 mm equivalent diameter) in the absence and presence of wind, respectively. These experiments were conducted with laser light. In this case, the CCD sensor was positioned in front of the capture zone, at a horizontal distance of 1.30 m and an elevation of 1.10 m above the ground (Figure 1a). The drop generating device was placed over the capture zone at an elevation of 1.45 m above the ground. In the LAW1 experiment the anemometer was located in the study region at an elevation of 1.10 m above the ground, near the capture zone but not invading it. The fan was placed at different horizontal distances from the drops, to create wind speeds of 1.84, 2.54, 4.54 and 6.95 m s⁻¹ during the complete drop falling trajectory.

Likewise, the LEC4 experiment was developed to produce large droplets in calm conditions (just as in LAC1), but using LED lighting and considering four observation points distributed along

the trajectory of the falling drops: the first observation point was located at the drop formation point (the tip of the hypodermic needle), and the other three were located at vertical distances of 0.50, 1.00 and 1.50 m.

Finally, small drops (with an average of 1.94 mm in equivalent diameter) were produced in the SEC9 experiment. In this experiment, calm wind conditions and LED lighting were used. Observation points were distributed along larger vertical distances than in LEC4 in order to characterize drops at or near terminal velocity. Nine observation points were considered: drop formation (zero distance), and vertical distances of 0.50, 1.00, 1.50, 2.50, 3.00, 4.00 and 4.28 m.

The camera exposure time was set to 33 ms. Preliminary tests were performed for each experiment to establish the optimum time between light pulses (Δt), leading to an adequate identification of drop position, and drop morphology. The experimental range in time between pulses was 0.5 – 6.0 ms, mainly depending on drop velocity. This time is very important, since the first light pulse captures the initial drop position and the second the final drop position of its displacement across the same image.

Image pre-processing

Image pre-processing was necessary in all cases. The images captured in LED lighting showed motion blur when the drop achieved speeds higher than 4 m s⁻¹. Blur was caused by the time during which the light pulse diffracts on each drop while it is recorded in an image (the response time of the LED light) and its fast motion. In order to correct this issue, LED images were subjected to an iterative deconvolution process. The Lucy-Richardson deconvolution technique (Lucy 1974) was implemented. This is one of the most common techniques used in image restoration due to its simplicity and efficiency. This model is based on maximizing the likelihood of the resulting image being an instance of the original image, with the assumption that its pixel intensities

conform to a Poisson distribution (Biggs and Andrews 1997; Shan et al. 2008). First, a two-dimensional filter is created from a correlation kernel to approximate the linear motion of the drops recorded in the image. The filter is a vector of horizontal and vertical movements, requiring the following input parameters: 1) the movement of the drop during its recorded displacement (in pixels, px), estimated by multiplying the LED response time (0.1 ms) by the drop velocity (in px ms^{-1}); 2) the blur angle, equivalent to the drop angle. Using the correlation kernel, the original image is restored. Figure 5a presents motion blur in an original drop image, while Figure 5b presents the same image processed with the Lucy-Richardson deconvolution technique, in which drop blur has been corrected.

In addition, the images captured in both laser and LED light were subjected to a digital treatment. For this purpose, algorithms developed in MatLab® v2015 were used with the aim of eliminating the gray tones in the background of the images and intensifying drop sharpness. This consisted of inverting the intensity and eliminating the excess of illumination applying a Gaussian high pass filter. Figure 6a presents a typical double-pulsed image captured with the CCD sensor in laser light (LAW1 experiment). Drops can be clearly observed in two different positions separated by a time Δt . Gray tones are displayed on the background image and in the drops, causing difficulty in particle detection with PTV. Figure 6b presents the same image after preprocessing. The background noise generated by excess lighting was eliminated, leaving the image in adequate conditions for submission to the PTV algorithm.

PTV image processing

The PTV-SED v2.1 software, originally developed to analyze the fall velocity of sedimentary particles in two-phase flows (Salinas-Tapia 2007), was used in this study. The algorithm was modified to accommodate the difference between sprinkler drop geometry and sediment

geometry. PTV operation comprises two sequential procedures. The first procedure implies improving image quality through spatial filtering. The second procedure implies detecting drops in each pulse following the five stages proposed by Salinas-Tapia et al. (2006): i) identify maximum and minimum intensity (black or white) over the drop image to determine its size; ii) from the intensity of pixels of the evaluated drop, a circular area is formed, determining the cross sectional drop area (a), and then the equivalent diameter (d) can be estimated using Equation 1; iii) from the cross-sectional drop area and pixel intensity, the coordinates (x , y) of the drop centroid are determined; iv) pairs of double-pulsed droplets are identified and the distance separating their centroids (Δx , Δy) is determined; and v) Drop velocity (v_x , v_y) is obtained using Equations 2.

$$d = 2\sqrt{a/\pi} \quad [1]$$

$$v_x = \left(\frac{\Delta x}{\Delta t} \right); \quad v_y = \left(\frac{\Delta y}{\Delta t} \right) \quad [2]$$

Initial software parameters were set according to capture conditions. The relationship between pixels and centimeters (magnification) was obtained from an internal calibration using a reference scale in mm. In each experiment, the magnification depended on the distance between the image plane (CCD camera) and the object plane (focus area). The distance separating the drop centroid between the first and the second pulse was estimated at each experiment, providing a first estimate of drop velocity variability. Figure 7 presents a sample double-pulsed drop image once processed. In addition, the horizontal and vertical distances separating the centroids are presented.

PTV-SED software uses Equations 2 to determine the module of the velocity vectors, and then builds velocity fields for a group of drops in free fall. The direction of the velocity vectors was

determined from the movement of the centroid of each double-pulsed drop. The software traced a line between both centroids, and drop angle was determined from the horizontal (vx) and vertical (vy) velocity components, using the following equation:

$$A = \tan^{-1}\left(\frac{vx}{vy}\right) \quad [3]$$

Drop parameters

The PTV algorithm was modified to add the determination of drop morphological parameters, including the longest drop chord (d_{max} , mm), the longest drop chord orthogonal to d_{max} (d_{min} , mm) and the canting angle (θ , in degrees). This is the angle between the horizontal axis and the longest drop chord, ranging from -90° to 90° . Figure 8 schematically illustrates the drop geometrical parameters used to characterize drop deformation. In this work, the chord ratio (C) was used to characterize the equilibrium shape and the deformation of water drops according to Chowdhury et al. (2015) as:

$$C = \frac{d_{min}}{d_{max}} \quad [4]$$

Drop statistics

Following digital processing, a statistic analysis was performed on the drop data set to obtain centrality and dispersion parameters such as the arithmetic mean ($\bar{m}$), the standard deviation (SD) and the coefficient of variation (CV), as from the following expressions:

$$\bar{m} = \frac{\sum_{i=1}^n m_i}{n} \quad [5]$$

$$SD = \sqrt{\frac{\sum_{i=1}^n (m_i - \bar{m})^2}{n-1}} \quad [6]$$

$$CV = \frac{SD}{\bar{m}} 100 \quad [7]$$

In the equations above, m can be represented by the equivalent diameter, velocity, drop angle, chord ratio or canting angle (d , v , A , C or θ , respectively) of a set of drops.

Numerical simulation

The governing equations in the movement of droplets in the air may be described by the ballistic theory (Fukui et al. 1980) as:

$$A_x = \frac{d^2x}{dt^2} = -\frac{3}{4} \frac{\rho_a}{\rho_w} \frac{Cd}{d} V(U_x - W_{sx}) \quad [8]$$

$$A_y = \frac{d^2y}{dt^2} = -\frac{3}{4} \frac{\rho_a}{\rho_w} \frac{Cd}{d} V(U_y - W_{sy}) \quad [9]$$

$$A_z = \frac{d^2z}{dt^2} = -\frac{3}{4} \frac{\rho_a}{\rho_w} \frac{Cd}{d} VU_z - g \quad [10]$$

where x , y , z are the coordinates referring to the origin of water drops (the tips of the hypodermic needles), t is the time coordinate, ρ_a the air density, ρ_w the water density, A the acceleration of the drop in the air, g is the gravitational acceleration, d the drop diameter, and Cd is a drag coefficient. Drop velocity (U) is equal to the vector of the drop in the air (V) plus the wind speed (Ws); this last is considered parallel to the ground surface. In order to solve the ballistic equations, a traditional fourth order Runge-Kutta method was used.

The ballistic simulation of drops emitted by sprinkler irrigation generally assumes that drops are solid spheres moving independently through the air. In this sense, the drag coefficient (Cd_s) has

been traditionally estimated as a function of the Reynolds (Re) number of a spherical drop, according to Okamura (1968) as:

$$Cd_s = \frac{33.3}{Re} - 0.0033 Re + 1.2, \quad Re \leq 100; \quad [11]$$

$$Cd_s = \frac{72.2}{Re} - 0.0000556 Re + 0.48, \quad 100 \leq Re \leq 1000; \quad [12]$$

$$Cd_s = 0.45, \quad Re \geq 1000; \quad [13]$$

Recently, a new model considering drop deformation has been proposed by Paniagua (2015) as:

$$Cd_e = Cd_s [1 + 2.322(C - 1)^2] \quad [14]$$

Where:

$$C = 1 - 0.1767 W_e \quad [15]$$

$$W_e = \frac{\rho_a v^2 d}{4\sigma} \quad [16]$$

Where v is the drop velocity relative to the wind, W_e is the Weber number, and σ is the drop surface tension.

This model (Cd_e) considers ellipsoidal drop deformation through the drop chord ratio (C) as a function of W_e and under the assumption that the drop moves at terminal velocity. Simulations were performed using the Sprinkler software (<https://github.com/jburguete/sprinkler>).

Drop trajectories were simulated using the Sphere and Ellipsoid drag equations. In all cases, simulations started with zero initial velocity (drop at the needle tip). Drops were characterized by their individual equivalent diameter and vertical distance from the drop release point to the point where they were photographed (average point of the two centromeres). Note that in Table 1 the approximate value of the measurement point is presented. This value is just an

approximation of the individual drop vertical distance. Comparisons were established between measured and simulated drop velocity using the sphere and ellipsoid models.

Results and Discussion

Table 1 presents key statistical parameters of drop diameter, chord ratio, canting angle, drop velocity and angle for each experiment, measuring point and wind speed. These results are analyzed in the following sections.

Effect of the illumination technique on drop characterization

Experiments LEC4 (at a distance of 0.5 m from the needles) and LAC1 (at a distance of 0.35 m from the needles) can be used to assess the effect of the illumination technique on drop size characterization. Both experiments were performed in windless conditions and using the same needle diameter. Results indicate that the average $\bar{d}$ in both experiments differed by less than 0.35%. A T-Test was performed in order to determine the probability that the measured drop diameters in LEC4 and LAC1 belong to the same data population. No statistically significant differences were found between the means of the two samples at the 95% confidence level.

In experiments LEC4 and SEC9 the response time of the LED lamp resulted relatively long (0.1 ms) in comparison with drop velocity. As a result, motion blur could be visually appreciated in images containing drops with velocities larger than 4 m s⁻¹. This is the case of experiments LEC4 at distances of 1.0 and 1.5 m and SEC9 at distances from 2.0 to 4.28 m. The effect was more intense as drops approached terminal velocity. In order to solve this problem, images were restored using the Lucy-Richardson deconvolution technique (Lucy 1974). Restored images from LEC4 showed differences in $\bar{d}$ lower than 0.18% when compared with focused drops (images without blur correction processing) measured at an elevation of 0.5 m. Furthermore, when analyzing the samples of d at each measurement point (0.0, 0.5, 1.0 and 1.5 m) in LEC4, the T-Test indicated that there was no statistically significant difference at the 95% confidence level. This validates the implementation of the image restoration technique.

Measured drop deformation under calm conditions

In experiment SEC9, drops were analyzed as they approached terminal velocity at an elevation of 4.28 m. Taking into account all nine measurement points in this experiment, the average $\bar{d}$ was 1.94 mm. The theoretical terminal velocity for this drop diameter is 6.43 m s⁻¹. The largest average velocity measured in this experiment was 6.48 m s⁻¹, with $\bar{d} = 1.99$ mm at the measurement point of 4.28 m.

In all SEC9 measurement points, equivalent diameters were measured in a range of 1.80 to 2.20 mm. The CV of $\bar{d}$ was about constant from 0 m to 3.5 m, with an average value of 2.58%. At elevations of 4.00 and 4.28 m the CV of $\bar{d}$ increased to 3.63% and 3.43%, respectively. This increment in $\bar{d}$ variability can be attributed to drop deformation as it falls.

The images captured at the origin (elevation of 0 m) in SEC9 showed how drops were released from the needles with a quasi-spherical shape ($\bar{C} = 0.98$, CV = 0.92%). Minor changes in drop geometry could be observed at that location, which were attributed to the detachment from the needle. In the following observation points (from 0.50 to 4.28 m), the average chord ratio was in a range of 0.96-0.98, while its CV ranged from 0.95 to 2.62%. These data indicate that drops entered an oscillatory deformation routine along their trajectory. It is well established in the literature that drops tend to reach equilibrium in their deformation as they approach terminal velocity (Muller et al. 2013, Beard et al. 2010; Chowdhury et al. 2015). The measured canting angle (θ) was very sensitive to drop size and shape. Average θ and its CV did not show a clear trend with measurement height and drop velocity. Nevertheless, the frequency distribution of θ indicates a clear pattern as drops approach terminal velocity. At the measuring points of 4.00 and 4.28 m, the canting angle showed a normal distribution around the maximum frequency of near horizontal ellipsoids, with an average standard deviation of 40° (data not shown). This is in partial

agreement with the results reported by Huang et al. (2008) and discussed by Beard et al. (2010) for droplets with diameters in the range of 2 - 8 mm measured at terminal velocity. These authors found that θ showed a symmetrical distribution with average at zero degrees and standard deviation of 7-8°. The large difference in the standard deviation seems to be associated to the small deformations observed in the small drops of SEC9 (identified by the high values of the chord ratio).

The situation was quite different in experiment LEC4, in which large drops were characterized at four elevations. In this experiment, the average $\bar{d}$ (considering all four measuring points) was 2.91 mm. The maximum average measured drop velocity was 4.91 m s⁻¹, while the theoretical terminal velocity for this average drop diameter is 7.85 m s⁻¹. As a consequence, drops were analyzed in the early phase of acceleration. In LEC4 the average $\bar{d}$ did not suffer relevant changes with the elevation of the measurement point. The highest variability in $\bar{d}$ was observed at 0 m elevation, with a CV of 3.23%. At the maximum elevation of 1.5 m the CV of $\bar{d}$ was 2.41%. At 0 m elevation, deformation was higher and more variable than in SEC9: the chord ratio averaged 0.95, ranging from 0.85 to 1.00, with a CV of 3.5%. As drops fell to elevations of 0.5, 1.0 and 1.5 m, drop shape became more spherical, with $\bar{C} = 0.97, 0.97$ and 0.98 , respectively, and with CV lower than 1.85%.

Measured drop deformation under wind conditions

Experiments LAC1 and LAW1 characterized large drops under calm and windy conditions, respectively. Both experiments were conducted at a vertical distance of 0.35 m from the tip of the needle. Considering all experimental conditions, the drop equivalent diameter presented an overall average of 2.94 mm, ranging from 2.51 mm to 3.35 mm, and presenting coefficients of variation lower than 5.53%. Histograms of drop diameter for these experiments are presented in Figure 9. Under no-wind conditions, a symmetrical, narrow distribution was found, with the

maximum frequency (42%) corresponding to diameters of about 3.0 mm. On the other hand, under wind conditions, wide, asymmetrical histograms were found, with much lower maximum frequency (24%, 24%, 25% and 29% for diameters of 3.2, 3.0, 2.9 and 3.10 mm, and for wind speeds of 1.84 m s⁻¹, 2.94 m s⁻¹, 4.54 m s⁻¹ and 6.95 m s⁻¹, respectively). Wind introduced heterogeneity in equivalent drop diameter through deformation. In all cases, the equivalent drop diameter was estimated from its area in the plane containing its centroid. As a consequence, deformation in its third dimension is ignored. This can explain the observed variations in equivalent drop diameter. Deformation increased with wind speed (particularly for 4.54 and 6.95 m s⁻¹). The average chord ratio decreased from 0.95 to 0.88 as wind increased from 1.84 to 6.95 m s⁻¹, and drop shape changed from a sphere to an ellipsoid. Drop oscillation modes for the fundamental harmonic have been described as axisymmetric, transverse, and horizontal (Beard et al. 2010; Chowdhury et al. 2015). The forces originating at the moment of drop detachment from the needle induced axisymmetric and transverse oscillation modes. In no-wind conditions, the canting angle presented an average of 14°, with a coefficient of variation of 494%. In the experimental wind speeds, the average canting angle increased up to 44°, and the coefficient of variation decreased to 103%. This behavior indicates that oscillations approach the transverse mode when drops are subjected to crosswind. Figure 10a shows the most deformed drops captured in LAC1 and LAW1 experiments, indicating the equivalent diameter, chord ratio and canting angle. Under calm conditions, the chord ratio was 0.81 and the canting angle was -19°. In the presence of wind, the largest deformation occurred for $Ws = 6.95 \text{ m s}^{-1}$, with a chord ratio of 0.75 and a canting angle of 43°. Figure 10b presents the least deformed drops for each experimental scenario. In these drops, the chord ratio ranged from 0.98 to 1.00.

Drop velocity was found to be in a range of 2.49-2.57 m s⁻¹ in all cases, primarily depending on the vertical position of the drop in the image frame. The variability of drop velocity was very small, with CV between 3.06% and 3.85%. Drop velocity did not show a clear trend with wind speed; however, alterations in drop trajectory were clearly visible: drop angle and its standard deviation increased with wind speed, while its CV decreased. In the absence of wind drop angles ranged between 0.00° and 0.73°.

Droplet velocity fields are presented for both experiments (five wind speeds) in Figure 11. In the absence of wind, the module of the velocity vector ranged between 2.28 and 2.76 m s⁻¹. Under windy conditions, drop velocity was more uniform, with a range of 2.49 to 2.56 m s⁻¹. An increase in the horizontal component of drop velocity (v_x , m s⁻¹) from 0.074 m s⁻¹ to 0.552 m s⁻¹ was obtained when the wind increased from 1.84 to 6.95 m s⁻¹, resulting in relevant horizontal drop displacement.

Figure 12 presents histograms of v_x under different wind conditions. As wind speed increased, the most frequent horizontal wind speed increased. At the same time, histograms became wider and the maximum frequency decreased. Under calm conditions, all horizontal drop velocities were in a range of 0.00 to -0.04 m s⁻¹, with a coefficient of variation of 0.72%.

Drop trajectory simulation: effect of the drag equation

A regression analysis was performed on measured vs. simulated drop velocity using the sphere and ellipsoid drag force models. Both simulation models explained 99.7% of the variability in drop velocity. Additionally, the resulting regression lines could not be distinguished from the 1:1 line at a 95% confidence level (Figure 13). The regression line of the ellipsoid model (Figure 13b) presented a slope closer to 1 and an intercept closer to 0.

The experimental conditions represent a transition in drop shape from a sphere (at near zero velocity) to an ellipsoid (at near terminal velocity). As a consequence, both drag models can effectively contribute to explain experimental drop kinetics. Although the ellipsoid model showed slightly better results than the sphere model, some scatter could be observed, particularly in wind conditions. Since the ellipsoid model assumes that drop deformation is in equilibrium (as tends to occur at terminal velocity), the oscillatory process experienced by falling drops during the initial steps of the trajectory (describing axisymmetric, transverse, and horizontal oscillation modes) may not be properly simulated. The introduction of complex phenomena such as the initial drop shape oscillations could further improve the predictive capacity of drag force models.

Implications for sprinkler irrigation modeling

Laboratory experiments permitted to control the variables determining drop morphology and dynamics in free fall and to analyze the process in detail. In open-field sprinkler irrigation, the situation is much more complex since additional variables intervene in the formation of drops, their movement in the air and their landing in different points of the field surface. Relevant knowledge gaps continue to exist in sprinkler drops. Ballistic theory is based on relevant hypotheses, which simplify the governing equations but result in relevant differences between observed and simulated irrigation performance (Carrión et al. 2001). As a consequence, ballistic models need empirical calibration coefficients (Carrión et al. 2001; Playán et al. 2006). One of such hypotheses is the assumption of spherical, independent drops (Fukui et al. 1980; Carrión et al. 2001). Burguete et al. (2007) discussed discrepancies between measured and simulated drop velocity, and pointed at the characterization of the drag force and the grouping and collision of drops. Recently, Paniagua (2015) presented the ellipsoid model tested in this paper, which resulted in very moderate improvements over the sphere model. In fact, in the experimental

conditions both models explained 99.7% of the variability in drop velocity. As a consequence, in the experimental range of drop diameter, drop velocity and wind speed the drag force model does not pose limitations to the quality of the simulations. More complex processes, such as the gradual breakup of the jet into drops, the reduction of the drag force due to drop grouping, or the breakup of large, unstable drops need to be clarified to further understand and model drop dynamics in sprinkler irrigation. These are indeed complex processes that will require relevant research efforts to produce analytical models not requiring ad-hoc calibration variables.

Conclusions

PTV with in-line volumetric illumination proved to be an effective technique to estimate the diameter, deformation and velocity of water droplets precipitated in the absence and presence of wind. The proposed experimental approach led to the measurement of drop size by illuminating a volume in the capture zone; furthermore, it allowed characterizing drop shape, which ranged from quasi-spherical drops to ellipsoids. PTV was assessed using two illumination techniques: a laser beam and an *ad hoc* LED lamp. The results of both illumination techniques could not be statistically distinguished. As a consequence, robust, low-cost LED lamps seem to be a clear option for future applications.

Drop size was controlled using hypodermic needles of different diameters for small and large drops. For instance, in large drops illuminated with a laser beam (LAC1 and LAW1), the overall average of the equivalent drop diameter was 2.94 mm; however, variations between 2.51 and 3.35 mm were observed in the data population. Dispersion in equivalent diameter increased with wind speed. In the absence of wind, drop deformation resulted in a range of chord ratios of 0.81-0.99, due to the forces originating at the moment of drop detachment from the needle, while in windy conditions the maximum deformation was $C = 0.70$, occurring under a Ws of 6.95 m s^{-1} . In the proposed methodology deformation is mathematically characterized by a chord ratio. However, it is important to note that the algorithm is applied to the two dimensions of the photograph. As a consequence, deformation in the third dimension was not explicitly considered, and could result in minor spurious variations of the equivalent drop diameter. Regarding drop dynamics, the total drop velocity showed similar values in windless and windy conditions, with average values ranging between 2.49 and 2.56 m s^{-1} . In addition, the vertical component of drop velocity was estimated. These data was very similar to the total drop velocity, with differences

not exceeding 0.003 m s^{-1} . The wind-induced increase in the horizontal component of drop velocity was accompanied by a relevant increase in the canting angle and the drop angle.

Experimental results permitted to assess the effect of the drag force model on the ballistic simulation of droplet dynamics. Two drag models, based on sphere and ellipsoid geometries were tested. Results indicated that in the experimental conditions both models effectively contribute to the accurate simulation of droplet dynamics, with the ellipsoid model providing a slightly better tracking of experimental results. The experimental conditions significantly differ from those of real sprinkler irrigation installations, where drop diameters are larger and drop velocities usually exceed terminal velocity. In real conditions, the ellipsoid equation could result much more adequate than the sphere equation. Additional experiments will be required for the adequate parametrization of the ellipsoid equation. Additional uncertainties of ballistic models, such as the distributed formation of droplets along the jet, the reduction of drag for groups of drops traveling together, or the breakup of large drops will also require attention in future works.

Optical techniques, such as the reported PTV application, can successfully determine the geometric and kinematic characteristics of water droplets under different experimental conditions. The robustness of the experimental equipment, particularly in combination with the developed LED lamp, announces future outdoor applications in real sprinkler irrigated fields. Such applications will provide insight on the governing processes, and data sets for the improvement of sprinkler simulation models.

Acknowledgements

Thanks are due to the *Centro Interamericano de Recursos del Agua* from the *Universidad Autónoma del Estado de México*, to the *Universidad Autónoma de Zacatecas* and to *Aula Dei* from the *Consejo Superior de Investigaciones Científicas* for the collaboration and support provided for the publication of this paper. Thanks are also due to CONACYT for providing a scholarship to Jesús Ramiro Félix-Félix to pursue doctoral studies.

References

- Abudi I, Carmi G, Berliner P (2012) Rainfall simulator for field runoff studies. *J. Hydrol* 454:76–81
- Adrian RJ (1991) Particle imaging techniques for experimental fluid mechanics. *Annu Rev Fluid Mech* 23(1):261–304
- Arnaez J, Lasanta T, Ruiz P, Ortigosa L (2007) Factors affecting runoff and erosion under simulated rainfall in Mediterranean vineyards. *Soil Till Res* 93:324–334
- Basahi JM, Fipps G, McFarland MJ (1998) Measuring droplet impact energy with piezoelectric film. *J Irrig Drain E-ASCE* 124(4):213–217
- Bautista-Capetillo C, Robles O, Salinas H, Playán E (2014) A particle tracking velocimetry technique for drop characterization in agricultural sprinklers. *Irrigation Sci* 32(6): 437–447
- Bautista-Capetillo C, Salvador R, Burguete J, Montero J, Tarjuelo J, Zapata N, González J, Playán E (2009) Comparing methodologies for the characterization of water drops emitted by an irrigation sprinkler. *T ASABE* 52(5):1493–1504
- Bautista-Capetillo C, Zavala M, Playán E (2012) Kinetic energy in sprinkler irrigation: different sources of drop diameter and velocity. *Irrigation Sci* 30(1):29–4
- Bavi A, Kashkuli HA, Boroomand S, Naser A, Albaji M (2009) Evaporation losses from sprinkler irrigation systems under various operating conditions. *Journal of Applied Sciences* 9(3):597–600
- Beard KV, Bringi VN, Thurai M (2010) A new understanding of raindrop shape. *Atmos Res* 97(4):396–415
- Biggs DS, Andrews M (1997) Acceleration of iterative image restoration algorithms. *Appl Optics* 36(8):1766–1775

- Blanquies J, Scharff M, Hallock B (2003) The design and construction of a rainfall simulator. International Erosion Control Association (IECA). In Proceedings of 34th Annual Conference and Expo, Las Vegas, USA p. 10
- Burguete J, Playán E, Montero J, Zapata N (2007) Improving drop size and velocity estimates of an optical disdrometer: Implications for sprinkler irrigation simulation. *T ASABE* 50(6): 2103–2116.
- Carrión P, Tarjuelo JM, Montero J (2001) SIRIAS: a simulation model for sprinkler irrigation. I Description of model. *Irrigation Sci.* 20(2):73–84
- Chowdhury MN, Testik FY, Hornack MC, Khan AA (2016) Free fall of water drops in laboratory rainfall simulations. *Atmos Res* 168:158-168
- Cruvinel PE, Vieira SR, Crestana S, Minatel ER, Mucheroni ML, Neto AT (1999) Image processing in automated measurements of raindrop size and distribution. *Comput Electron Agric* 23:205–217
- Dechmi F, Playán E, Cavero J, Martínez-Cob A, Faci JM (2004) A coupled crop and solid set sprinkler simulation model: I. Model development. *J Irrig Drain E-ASCE* 130(6):499–510
- Eigel JD, Moore ID (1983) A simplified technique for measuring raindrop size and distribution. *T ASAE* 26(4):1079-1084
- Fukui Y, Nakanishi K, Okamura S (1980) Computer evaluation of sprinkler irrigation uniformity. *Irrigation Sci* 2:23–32
- Ge M, Wu P, Zhu D, Ames DP (2016) Comparison between sprinkler irrigation and natural rainfall based on droplet diameter. *Span J Agric Res* 14(1):1201
- Hauser D, Amayenc P, Nutten B, Waldteufel P (1984) A new optical instrument for simultaneous measurement of raindrop diameter and fall speed distributions. *J Atmos Ocean Tech* 1:256–269

- Huang GJ, Bringi VN, Thurai M (2008) Orientation angle distributions of drops after an 80-m fall using a 2D video disdrometer. *J Atmos Ocean Tech* 25(9):1717-1723.
- Jensen KD (2004) Flow measurements. *J Braz Soc Mech Sci* 26:400-419
- Kathiravelu G, Lucke T, Nichols P (2016) Rain Drop Measurement Techniques: A Review. *Water* 8(1):1-29
- Keller J, Bliesner RD (1990) *Sprinkle and Trickle Irrigation*. Van Nostrand Reinhold, New York
- Kincaid DC (1996) Spraydrop kinetic energy from irrigation sprinklers. *T ASAE* 39(3):847-853
- King BA, Bjorneberg DL (2012) Droplet kinetic energy of moving spray-plate center-pivot irrigation sprinklers. *T ASABE* 55(2):505-512
- King BA, Winward TW, Bjorneberg DL (2010) Laser precipitation monitor for measurement of drop size and velocity of moving spray-plate sprinklers. *Appl Eng Agric* 26(2):263-271
- Kohl RA (1974) Drop size distribution from medium-sized agricultural sprinklers. *T ASAE* 17(4):690-693
- Laws JO, Parsons DA (1943) The relation of raindrop-size to intensity. *Eos, Transactions American Geophysical Union* 24(2):452-460
- Li J, Kawano H, and Yu K (1994) Droplet size distributions from different shaped sprinkler nozzles. *T ASAE* 37(6):1871-1878
- Li J, Kawano H (1995) Simulating water-drop movement from noncircular sprinkler nozzles. *J Irrig Drain Div ASCE* 121:152-158
- Li Y, Bai G, Yan H (2015) Development and validation of a modified model to simulate the sprinkler water distribution. *Comput Electron Agr* 111:38-47
- Liu XC, Gao TC, Liu L (2014) A video precipitation sensor for imaging and velocimetry of hydrometeors. *Atmospheric Measurement Techniques* 7(7):2037-2046

- Lorenzini G, De Wrachien D (2005) Performance assessment of sprinkler irrigation systems: A new indicator for spray evaporation losses. *Irrig Drain* 54(3):295-305
- Lowe EJ (1892) Rain drops. *Q J Roy Meteor Soc* 18(84):242-245.
- Lucy LB (1974) An iterative technique for the rectification of observed distributions. *The astronomical journal* 79(6):745-754
- Magarvey RH (1956) Stain method of drop size determination. *J Meteorol* 14:182-184
- Montero J, Tarjuelo JM, Carrión P (2003) Sprinkler droplet size distribution measured with an optical spectropluviometer. *Irrigation Sci* 22:47-56
- Müller S, Szakáll M, Mitra SK, Diehl K, Borrmann S (2013) Shapes and oscillations of raindrops with reduced surface tensions: Measurements at the Mainz vertical wind tunnel. *Atmos Res* 119:38-45
- Okamura S (1968) Theoretical study on sprinkler sprays. *Trans JSIDRE* 26:49-55
- Paniagua P (2015) Mejora del riego por aspersión en parcela: Caracterización de aspersores a baja presión, estudio de diferentes sistemas de medición de gotas y análisis del modelo balístico. Dissertation, CSIC - Universidad de Zaragoza
- Peña PE (2007) Tecnificación del riego presurizado. Manual para Diseño de Zonas de Riego Pequeñas. IMTA, México, pp 1-89
- Playán E, Zapata N, Faci JM, Tolosa D, Lacueva, JL, Pelegrín J, Lafita A (2006) Assessing sprinkler irrigation uniformity using a ballistic simulation model. *Agr Water Manage* 84(1):89-100
- Salinas-Tapia H, García AJ, Moreno HD, Barrientos GB (2006) Particle tracking velocimetry (PTV) algorithm for non-uniform and non-spherical particles. *Proceedings, Electronics, Robotics and Automotive Mechanics Conference, CERMA* 2:322-327
- Salinas-Tapia H (2007) Determinación de parámetros para flujo bi-fásico (sólido-líquido) por medio de técnicas ópticas. Dissertation, Universidad Autónoma del Estado de México.

- Salinas-Tapia H, Robles-Rovelo CO, Chávez-Carlos D, Bautista-Capetillo CF (2014) Caracterización geométrica y cinemática de un chorro pulverizado empleando la técnica óptica PTV. *Tecnología y ciencias del agua* 5(3):125-140
- Salvador R, Bautista-Capetillo C, Burguete J, Zapata N, Playán E (2009) A photographic methodology for drop characterization in agricultural sprinklers. *Irrigation Sci* 27(4):307-317.
- Shan Q, Jia J, Agarwala A (2008) High-quality motion deblurring from a single image. *ACM T Graphic* 27(3) p. 73
- Smits AJ, Lim TT (2000) *Flow Visualization: Techniques and Examples*. Imperial College Press, London
- Sudheer KP, Panda RK (2000) Digital image processing for determining drop sizes from irrigation spray nozzles. *Agr Water Manage* 45:159-167
- Thompson AL, James LG (1985) Water droplet impact and its effect on infiltration. *T ASABE* 28(5):1506-1510
- Van Dyke M (1982) *An Album of Fluid Motion*. Parabolic Press, Stanford, CA
- Vories ED, von Bernuth RD, Mickelson RH (1987) Simulating sprinkler performance in wind. *J Irrig Drainage Div. ASCE* 113(1):119-130
- Wu D, Guillemin D, Marshall AW (2007) A modeling basis for predicting the initial sprinkler spray. *Fire Safety J* 42(4):283-294
- Yazar A (1984) Evaporation and drift losses from sprinkler irrigation systems under various operating conditions. *Agr Water Manage* 8(4):439-449.

List of tables

Table 1. *Statistical characterization of the drops analyzed in each experiment, classified by elevation and wind speed. Results are presented for drop diameter, chord ratio, canting angle, velocity and angle. For each variable, the average and coefficient of variation (%) are presented.*

List of figures

Figure 1. *Experimental setup for drop characterization using the PTV technique with two types of illumination: a) Laser; and b) LED lamp. The figure presents the different elements: computer, illumination, synchronizer, optical equipment, CCD camera, drop generator, fan and anemometer.*

Figure 2. *Laser light sheet diffracting a water droplet at different positions: outside the centroid (a & b) and at the centroid drop (c).*

Figure 3. *Average wind speed measured with the anemometer at the three fan power levels and at different horizontal distances.*

Figure 4. *Cross sectional wind speed fields created by the fan operating at level 1: a) at a horizontal distance of 3 m; and b) at a horizontal distance of 2 m.*

Figure 5. *Motion blur correction from a double-pulsed image using LED light: a) image of a drop captured near at terminal velocity (6.48 m s^{-1}); and b) image restored using the Lucy-Richardson deconvolution technique.*

Figure 6. *Drop pre-processing in experiment LAW1: a) typical double-pulsed image captured by the CCD; and b) pre-processed image.*

Figure 7. *Drop captured at two different times in experiment LAW1 (t , $t+\Delta t$). The location of the drop centroid at each time is presented, along with the horizontal (Δx) and vertical (Δy) centroid displacement.*

Figure 8. *Geometrical parameters used to characterize drop shape: longest drop chord ($d_{\max}$), longest drop chord orthogonal to $d_{\max}$ ($d_{\min}$) and canting angle (θ).*

Figure 9. *Histograms of measured drop equivalent diameter for experiments LAC1 and LAW1, for different values of wind speed.*

Figure 10. Drop captures in experiments LAC1 and LAW1. Deformed (a) and quasi-circular (b) large drops are presented for wind speeds ranging from 0 to 6.95 m s^{-1} . The measured equivalent diameter, chord ratio and canting angle are indicated for each drop.

Figure 11. Velocity fields of large drops in windless conditions and in the presence of wind, as measured in experiments LAC1 and LAW1 (with velocities of 1.84 m s^{-1} , 2.94 m s^{-1} , 4.54 m s^{-1} and 6.95 m s^{-1}). Eighty vectors are represented at each plot. A velocity scale and an indication of the drop trajectory are presented at the lower right corner.

Figure 12. Histograms of measured drop horizontal velocity component (v_x) for experiment LAW1, classified by wind speed.

Figure 13. Scatter plot of simulated vs. measured module of the drop velocity vector for the LAC1, LAW1, LEC1 and SEC9 experiments. Regression lines, equations, and coefficients of determination (R^2) are presented for both dependent variables. Simulations were performed using Sphere (a) and Ellipsoid (b) drag equations.

1 **Table 1.** Statistical characterization of the drops analyzed in each experiment, classified by elevation and wind speed. Results are presented for drop
2 diameter, chord ratio, canting angle, velocity and angle. For each variable, the average and coefficient of variation (%) are presented.

Experiment	Measuring point (m)	Wind speed (m s ⁻¹)	Drop diameter (mm)		Chord ratio (adm)		Canting angle (°)		Drop velocity (m s ⁻¹)		Drop angle (°)	
			$\bar{d}$	CV (%)	$\bar{C}$	CV (%)	$\bar{\theta}$	CV (%)	$\bar{v}$	CV (%)	$\bar{A}$	CV (%)
SEC9	0.00	0.00	1.90	2.50	0.98	0.92	1.32	3830.4	0.71	32.18	1.86	47.53
	0.50	0.00	1.98	2.67	0.97	1.56	18.76	424.4	3.02	1.72	0.15	79.97
	1.00	0.00	1.92	2.65	0.98	0.95	27.34	175.7	4.01	0.89	0.42	52.73
	1.50	0.00	1.97	2.57	0.97	2.62	-9.51	-689.6	4.66	1.37	0.61	62.73
	2.50	0.00	1.94	2.77	0.97	1.87	14.89	291.3	5.55	2.96	0.69	64.52
	3.00	0.00	1.90	2.38	0.97	1.43	11.33	471.7	5.70	1.81	1.13	36.72
	3.50	0.00	1.91	2.49	0.97	1.82	6.90	657.9	6.13	2.75	0.85	56.29
	4.00	0.00	1.97	3.63	0.96	2.05	-3.94	-999.2	6.29	3.83	0.63	66.01
	4.28	0.00	1.99	3.43	0.97	1.93	-7.58	-552.5	6.48	1.95	0.32	76.60
LEC4	0.00	0.00	2.90	3.23	0.95	3.50	10.71	598.9	0.68	18.98	1.64	70.61
	0.50	0.00	2.92	2.59	0.97	1.85	-2.66	-2126	2.96	1.85	0.78	64.61
	1.00	0.00	2.92	2.99	0.97	1.81	8.414	611.4	4.15	1.06	0.51	49.87
	1.50	0.00	2.91	2.41	0.98	1.53	-11.7	-519	4.91	0.95	0.41	59.82
LAC1	0.35	0.00	2.92	3.07	0.94	3.79	13.78	493.8	2.53	2.85	0.19	75.88
LAW1	0.35	1.84	2.96	5.26	0.95	3.24	27.48	160.8	2.52	3.31	4.47	23.74
	0.35	2.94	2.91	4.61	0.93	4.72	29.07	182.8	2.53	3.46	4.77	29.30
	0.35	4.54	2.94	5.53	0.90	4.47	42.56	108.1	2.49	3.06	6.88	28.88
	0.35	6.95	2.98	4.61	0.88	6.40	44.26	103.1	2.53	3.85	8.27	24.54

3

Figure 1. Experimental setup for drop characterization using the PTV technique with two types of illumination: a) Laser; and b) LED lamp. The figure presents the different elements: computer, illumination, synchronizer, optical equipment, CCD camera, drop generator, fan and anemometer.

Figure 2. Laser light sheet diffracting a water droplet at different positions: outside the centroid (a & b) and at the centroid drop (c).

Figure 3. Average wind speed measured with the anemometer at the three fan power levels and at different horizontal distances.

Figure 4. Cross sectional wind speed fields created by the fan operating at level 1: a) at a horizontal distance of 3 m; and b) at a horizontal distance of 2 m.

Figure 5. Motion blur correction from a double-pulsed image using LED light: a) image of a drop captured near at terminal velocity (6.48 m s^{-1}); and b) image restored using the Lucy-Richardson deconvolution technique.

Figure 6. Drop pre-processing in experiment LAW1: a) typical double-pulsed image captured by the CCD; and b) pre-processed image.

Figure 7. Drop captured at two different times in experiment LAW1 (t , $t+\Delta t$). The location of the drop centroid at each time is presented, along with the horizontal (Δx) and vertical (Δy) centroid displacement.

Figure 8. Geometrical parameters used to characterize drop shape: longest drop chord (d_{max}), longest drop chord orthogonal to d_{max} (d_{min}) and canting angle (θ).

Figure 9. Histograms of measured drop equivalent diameter for experiments LAC1 and LAW1, for different values of wind speed.

Figure 10. Drop captures in experiments LAC1 and LAW1. Deformed (a) and quasi-circular (b) large drops are presented for wind speeds ranging from 0 to 6.95 m s⁻¹. The measured equivalent diameter, chord ratio and canting angle are indicated for each drop.

Figure 11. Velocity fields of large drops in windless conditions and in the presence of wind, as measured in experiments LAC1 and LAW1 (with velocities of 1.84 m s^{-1} , 2.94 m s^{-1} , 4.54 m s^{-1} and 6.95 m s^{-1}). Eighty vectors are represented at each plot. A velocity scale and an indication of the drop trajectory are presented at the lower right corner.

Figure 12. Histograms of measured drop horizontal velocity component (vx) for experiment LAW1, classified by wind speed.

Figure 13. Scatter plot of simulated vs. measured module of the drop velocity vector for the LAC1, LAW1, LEC1 and SEC9 experiments. Regression lines, equations, and coefficients of determination (R^2) are presented for both dependent variables. Simulations were performed using Sphere (a) and Ellipsoid (b) drag equations.