EVAPORATION LOSSES IN IRRIGATION SPRINKLERS: AN OVERVIEW

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Abstract: *A thorough understanding of the factors affecting spray flow and evaporation losses in sprinkler irrigation is important for developing appropriate water conservation strategies. To properly tackle this problem, relevant theoretical and experimental studies have been carried out during the second half of the last century. Notwithstanding all these efforts, the phenomenon of aerial evaporation of droplets exiting from a nozzle has not been fully understood yet and something new as to be added to the description of the process to reach a better assessment of the events. To this end, a mathematical model for irrigation sprinkler droplet ballistics, based on a simplified dynamic approach to the phenomenon, has been presented. The model proves to fully match the kinematic results obtained by more complicated procedures. Moreover, field trials showed the model to reliably estimate spray evaporation losses caused by environmental conditions. Further analytical and experimental activities are needed to gain a better understanding of water flow and waste in sprinkler irrigation practice.*
Key words*: Sprinkler irrigation, water droplet, evaporation.*

INTRODUCTION

Scientific literature concerning irrigation systems (Larry, 1988; Keller & Bliesner, 1990; Schultz & De Wrachien, 2002) is mainly focused on the optimisation of water distribution on the soil, generally neglecting other aspects such as aerial evaporation in sprinkler irrigation. One of the causes of this behaviour is a scarce agreement among scientists for what concerns a clear and univocal definition of the phenomenon causing water losses during irrigation and of the parameters affecting its dynamics. So, spray evaporation of water droplets in sprinkler practice - that is water loss in the aerial path covered by a droplet exiting from a nozzle before it reaches the soil surface - was quantified with values ranging from 2 % or less up to 40 % or more (James, 1996; Tarjuelo *et al.*, 2000).

Since Christiansen's (1942) now classical work, important studies (theoretical and experimental ones) have been carried out to determine sprinkler spray flow and losses under various climatic and operational conditions (Mather 1950, Frost & Schwalen, 1955; Wiser, 1959; Inoue, 1963; Kraus, 1966).

STATISTICAL AND THEORETICAL APPROACHES

Basically there are two approaches (statistical and physical mathematical) available to solve spray flow and waste problems (Seginer *et al.* 1991). In the first, the measured evaporation losses are related to environmental and operational parameters. The second approach resorts to models which link equations ruling water droplet evaporation with particle dynamics theory.

1. The statistical approach

The mutual interactions of all the factors affecting the aerial path of and losses to a water droplet (among which are worth mentioning dimension of the droplet, air temperature, air friction, relative humidity, solar radiation, wind velocity) leaving the sprinkler nozzle make it very hard to work out a proper description and assessment of the phenomena. The problem is particularly acute with respect to drift, where it seems to be very difficult to distinguish between the drift and the distortion of the distribution pattern.

Resorting to statistical (empirical) formulae becomes so often the only way to circumvent the difficulties, not to say the impossibilities, that analytical procedure would imply.

An important work along this line is that of Frost and Schwalen (1955), resulting in a monogram relating spray losses to air relative humidity, air temperature, wind speed, nozzle diameter and nozzle pressure. In that and in other studies, losses were recorded as percent of application, and the results have been statistically analysed in accordance with the model chosen for the process.

Seginer (1971) worked out a regression model of water loss during sprinkling as a function of various meteorological and operational conditions. Seginer's models, strictly speaking, applies, mainly, to homogeneous areas, where transfer phenomena may be considered one dimensional, in the vertical direction. Nevertheless, it is also useful in dealing with the effect of application rate on the evaporation in field experimental plots.

Yazar (1984), testing with sprinkler laterals, obtained:

$$E = 0.389\mathrm{e}^{(0.18W)}\left(e_s - e_a\right)^{0.7} \qquad (1)$$

where: E is the percentage of discharged flow lost due to evaporation in %; W is the wind speed in ms^{-1}; and e_s and e_a are the saturation vapour pressure and the actual vapour pressure of the air in kPa, respectively. Different expressions are available for the assessment of the vapour pressure deficit $\left(e_s - e_a\right)$. Murray (1967), defined vapour pressure deficit as:

$$\left(e_s - e_a\right) = 0.611\exp\left(\frac{17.27T_a}{237.3 + T_a}\right)\left(1 - \frac{H}{100}\right) \qquad (2)$$

where: T_a is the dry bulb temperature °C; and H the relative humidity %.

Campbell Scientific (1995) proposed the following formula:

$$\left(e_s - e_a\right) = 0.00066\left(1 + 0.00115T_w\right)\left(T_a - T_w\right)P \qquad (3)$$

where: T_w is the wet-bulb temperature in °C; and while P represents the air pressure in kPa.

Considering the wind as the only factor affecting evaporation losses in a test with a sprinkler lateral, Yazar (1984) obtained the following equation

$$E = 1.68\mathrm{e}^{0.29W} \qquad (4)$$

Tarjuelo *et al.* (2000), carried out a set of experimental investigations for estimating drift and evaporation losses during sprinkler irrigation events. Various sprinkler-nozzle-riser height combinations were used and the variation of evaporation and weather conditions were measured during the tests which allowed the authors to define the following linear statistical model for water losses prediction in sprinkler practice:

$$L = c_1P + c_2\left(e_s - e_a\right)^{0.5} + c_3W + e \qquad (5)$$

where: L is the evaporation and drift losses in %; c_1, c_2 and c_3 are regression coefficients, and *e* is the experimental error. The model proved to be a useful tool to determine the irrigation timing as a function of environmental and operational conditions in order to minimise evaporation and drift losses.

2. The physical-mathematical approach

There are, at least, three important benefits to be gained from mathematical modelling of the spray droplet transport and evaporation processes, as well as of any physical process. The first of these is that the model development process forces recognition of knowledge gaps. When such gaps occur, research can be initiated to supply the missing pieces. The second benefit arises because a good model must always be experimentally verified. The verification process forces a close examination of any differences between what is predicted and what actually occurs. Finally, a proven model can be a valuable engineering and research tool.

Kinzer and Gunn (1951), modelled evaporation for droplets falling at terminal velocity, just in terms of heat and mass transfer, neglecting the dynamic actions affecting the flight of the droplets. Their results are focused on mass-change effects in a few Reynolds number intervals.

Formally,

$$\frac{\mathrm{d}m}{\mathrm{d}t} = 4\pi r^2 K\left(\frac{\mathrm{d}\rho_v}{\mathrm{d}R}\right)_r \tag{6}$$

where: m is the mass of the droplet in kg; r is the constant outer radius of the droplet in m; K is the diffusivity of vapour in air in $\mathrm{m^2s^{-1}}$ and $\left(\mathrm{d}\rho_v / \mathrm{d}R\right)_a$ is the vapour-density gradient established at the surface of the droplet in kg m^{-4}; ρ_v is the vapour density in kg m^{-3} and R the radial coordinate in m; and t is time in s.

Ranz and Marshall (1952), studied the evaporation of droplets in connection with spray drying and presented an equation for molecular transfer rate during evaporation along the flight path of the droplet. Goering *et al.* (1972) , starting from the Marshall's (1954) equation, arrived at the following formula for computing the change in droplet diameter *D* due to evaporation, based on heat and mass transfer analogy:

$$\frac{\mathrm{d}D}{\mathrm{d}t} = -2\left(\frac{M_v}{M_m}\right)\left(\frac{K}{D}\right)\left(\frac{\rho}{\rho_d}\right)\left(\frac{\Delta P}{P_f}\right)Nu' \tag{7}$$

where: M_v is the molecular weight of vapour in g; M_m is the molecular weight of air in g; K is the diffusivity of vapour in air in $\mathrm{m^2 s^{-1}}$; ρ is the density of air in kg m^{-3}; ρ_d is the density of the droplet in kg m^{-3}; ΔP is the difference in Pa between the saturation pressure at the wet bulb temperature of air and the vapour pressure at the dry bulb temperature; P_f is the partial pressure of air in Pa; and Nu' is a specially defined Nusselt number for mass transfer. This formula was obtained not as the result of an analytical procedure but by utilising empirical formulae from different authors for the definition of the parameters involved. The experimental data of Roth and Porterfield (1965**)** were used to verify the model. Williamsom and Threadfill (1974) also used the mass diffusion equation in a form similar to the above equation. Williamson and Thereadfill concluded that the results of their model, when compared to measured horizontal and vertical displacements and change in droplet diameter due to evaporation, were accurate under experimental conditions. The study was conducted with droplet diameters from 0.1 to 0.2 mm.

In the study by Seginer (1965) the following differential equation, describing water droplet ballistics in an interesting original way using an empirical drag coefficient C_q in $\mathrm{m}^{1-q}\mathrm{s}^{q-2}$ and an empirical non-dimensional exponent *q*, was developed:

$$g - \frac{\mathrm{d}V}{\mathrm{d}t} = C_q V^q \tag{8}$$

where: g is the acceleration of gravity in $\mathrm{ms^{-2}}$, $\mathrm{d}V / \mathrm{d}t$ is the resultant acceleration of the droplet in $\mathrm{ms^{-2}}$, *V* the velocity in $\mathrm{ms^{-1}}$ and *t* is the time in s. This equation can be solved by means of finite difference numerical techniques to predict velocity and travel distance for small time intervals.

Okamura and Nakanishi (1969) used a similar approach based on momentum and drag coefficients to determine the pattern of a sprinkler under wind conditions.

James (1981) adopted the Seginer's model to estimate the kinetic energy of water applied and arrived at the conclusion that the kinetic energy per unit volume of water applied is a sole function of the droplet impact velocity. The same approach was chosen in Hinkle (1991) , where the non dimensional exponent *q* was defined as a function of droplet size and velocity.

Edling (1985) developed a model, based on the impulse momentum principle, to estimate kinetic energy, evaporation and wind drift of droplet from low pressure irrigation sprinkler. The author's aim was to determine the influence of design and meteorological parameters on droplet behaviour. Droplet size, height, flow rate and deflection plate angle of the nozzle, air temperature and humidity, wind direction and velocity were assumed as input data. The model showed a rapid depletion of evaporation and drift losses when the drop diameter increases, as well as a high dependency of losses on wind speed and riser height. Edling inferred from his experiences that drop evaporation in sprinkler irrigation is almost negligible for a droplet diameter of 1.5-2 mm.

The same results arrived at Kohl *et al.* (1987), on the basis of field measurements and Kincaid and Longley (1989), by means of theoretical investigations. Kincaid and Longley's model combined the heat and mass transfer analogy with the particle dynamics approach to account for the effects of wind drift. The authors' overall objective was to develop a model able to predict droplet losses and assess the role of water temperature in the evaporation process.

Evaporation loss is taken as the difference between the amount of water leaving the sprinkler nozzle and measured with a grid of catch vessels. When using this concept, it must be assumed that the entire difference between the discharged volume and the collected one should not be considered as losses. The reason is that the microclimate generated above the crop during irrigation and the water retention by crop itself imply, among other effects, substantial crop transpiration depletion.

To this end, Thompson *et al.* (1993, 1997) proposed a model suitable for assessing water losses during sprinkler irrigation of a plant canopy under field conditions. The procedure combines equations governing water droplet evaporation - based on the heat and mass transfer analogy - and droplet ballistics (three - dimensional droplet trajectory equations) with a plant-environment energy model. The latter includes droplet heat and water exchange above the canopy, along with the energy associated with cool water impinging on the canopy and soil.

To avoid the difficulties that a univocal analytical procedure would imply, the authors resorted to empirical formulae which were able to give results in reasonable agreement with field measurements carried out in experimental plots equipped, mainly with low pressure sprinkling systems and lysimeters.

The model was used to quantify the partitioning of water losses between droplet evaporation from wetted canopy and soil, and transpiration during irrigation. The model showed that evaporation losses increased rapidly when droplet diameter decreased, as a result of the greater exposed surface area of the smaller drops. Moreover, comparisons between model outcomes and experimental measurements indicated that canopy evaporation amounted to a great extent (more than 60%) of the total spray losses. The studies by Thompson *et al.*, are considered by specialists to be among the most relevant thematic researches ever made in this field.

The effect of sprinkler evaporation on the microclimate and plant species however, was previously investigated by different researchers, among which is worth mentioning: Frost and Schwallen (1960), Kraus (1966), Wiersma (1970), Kohl and Wright (1974), Longley *et al.* (1983), Silva and James (1988).

Small droplet behaviour (order of magnitude of μm) was analysed by many authors, starting from Ranz and Marshall (1952), who based their investigations on Fröessling's (1938) boundary layer equations and the equation for heat and transfer analogy.

Later on, Mokeba *et al.* (1997) proposed a procedure accounting for three dimensional effects of turbulence on a spray droplet motion. More recently De Lima *et al.* (2002**)** worked out a model of a water droplet moving downwards from a rainfall simulator nozzle, which pays particular care to the final mean kinetic energy of small droplets affected in their motion by the action of the wind.

Over the last 25 years, a significant modelling and data collection effort has been undertaken, mainly, by the USDA Forest Service and its co-operators to develop accurate, validated models (spray drift models) to predict the small droplet behaviour (up to 10 μm or less) in both sprinkler irrigation practice and chemical spray aerial applications (Teske *et al.* , 1998 a, 1998 b) . The models are based on both the Lagrangian trajectory analysis of the spray material and Gaussian slanted-plume approach (Teske *et al.*, 2002). Reed (1953) first developed the equations of motion for spray material released from nozzles on an aircraft. Later on, other researchers independently developed their own spray drift models, or contributed essential pieces to the modelling process. These authors include Williamson and Threadgill (1974), Bache and Sayer (1975), Trayford and Welch (1977), Frost and Huang (1981), Saputro and Smith (1990), and Wallace *et al.* (1995). Lagrangian modelling is now used to simulate other phenomena such as chemical/biological cloud impact on helicopters (Quackenbush *et al.,* 1997) and jettisoning of jet fuel at altitude (Quackenbush *et al.*, 1994). Recent extensive field studies (Hewitt *et al.* 2002), and model validation efforts (Bird *et al.*, 2002) confirmed the predictive capability of the Lagrangian computational procedure that constitutes the core of the spray drift models. The last versions of the package include atmospheric stability effects, vortical decay, soil characteristics and features, plant canopy and the aerial release of dry materials (Teske *et al.*, 2003).

Among the different procedures now available, the heat and mass transfer approach offers a sound basis for the assessment of evaporation from falling droplets and the results are in reasonable agreement with experimental data for Reynolds numbers, generally, lower than 1000 that fall, mainly, under the laminar and/or intermediate flow laws.

More recently, Lorenzini (2004) and Lorenzini and De Wrachien (2003,2004,2005) proposed a model that accounts, mainly, the effects of air friction on droplet evaporation, which is relevant in the turbulent flow law (Reynolds numbers greater that 1000). The model proved to fully match the kinematic results obtained by more complicated procedures and to work out ready to apply formulae suitable to assess the contribution given to the droplet evaporation by the dynamic phenomena that accompany its aerial path from the sprinkler nozzle to the ground.

EXPERIMENTAL STUDIES ON SPRAY FLOW AND EVAPORATION LOSSES

Measurement problems exist when trying to quantify spray losses and validate flow and evaporation models in sprinkler irrigation practice. As previously stated, evaporation loss is taken as the difference between the amount of water leaving the nozzle and measured with a grid network of catch cans. Accurate measurement of water that reaches the ground is very tough with high wind because drift greatly increases the area where measurement is needed. Moreover, evaporation from the collection units is very hard to assess. Investigators have applied corrections to account for these errors, but accurate evaluations are difficult to achieve (Jensen, 1980). Related to this issue, interesting results were obtained by Zanon and Testezlaf (1995) and Zanon *et al.* (2000), who studied problems of experimental techniques for automatic systems of water collection at ground level and the methods of measurement of the water collected, in order to reduce experimental errors.

Pertinent theoretical-experimental results were also obtained by Bilanski and Kidder (1958), who investigated the external and internal factors affecting spatial uniformity of irrigation water, taking into account Christiansen's coefficient of distribution. Solomon (1979) analysed the beta distribution of individual rotating sprinklers in the presence of external factors.

Tackling the same subject, Le Gat and Molle (2000) devised a model, free from any ballistic assumption, suitable to describe the application pattern of a single rotating sprinkler, and to account for its performance in both windy and zero wind conditions, using a combination of beta functions. The main practical interest of the model lays on the fact that, once the pertinent parameters have been estimated, the depth of water falling on any sufficiently small surface element can be computed using a single ready-to-apply equation. The model can be also easily implemented in a larger module suitable to simulate the water application under centre pivots and moving laterals.

Probability water application curves have been previously analysed by many researchers. Seginer *et al*. (1991) using water application measurements for different wind speeds, calculated interpolated maps corrected for evaporation and drift losses. Han *et al.* (1994) developed a simulation model using water application curves measured in different directions related to the wind under single rotating sprinklers. Generally, in this approach probability distribution curves of water application are determined in different conditions and are identified by the type of distribution function and their mean and standard deviation.

Some investigations focused on radial or square-grid distribution of the catch cans in different environmental conditions. Bilanski and Kidder (1958) studied the effects of various sprinkler components, including pressure and nozzle size, on the pattern shape and radius. Seginer (1963) developed standardised patterns and related the pattern radius to the pressure head for certain nozzle sizes. Solomon *et al.* (1980) used a clustering algorithm to group pattern test data into typical standards shapes and used pattern radius to define a relative distance from the sprinkler. Kincard (1982) proposed an analytical approach suitable to describe the combined effects of nozzle size, pressure and nozzle discharge on sprinkler pattern radius. The procedure can be used to assess the performance of different sprinklers or nozzles and to determine the effects of the sprinkler characteristics (nozzle height, jet momentum flux and angle) on pattern radius.. Tarjuelo *et al.* (2000) recently carried out an experimental investigation on water losses in sprinkler irrigation due to evaporation and wind drift, without closely examining the effect of the surrounding air temperature.

The sizes of water droplets from spray nozzles bear on important areas of irrigation experimental study, including the extent of wind drift and evaporation losses, distortions of spray patterns by the wind and the reduction of the soil infiltration rate due to drop impact on the soil surface. Moreover, knowing the droplet distribution within the jet and along a radius could help anticipate their path related to environmental conditions.

To enter into details, research has shown that small droplets lead to distortion of spray patterns by wind as well as to water loss due to wind drift and evaporation (Thomspon *et al.* 1986) . Large droplets may lead to a reduced soil infiltration rate through soil surface disruption caused by droplet impact (Mohammad & Kohl, 1986). Nozzle configuration and water pressure are both important factors in determining droplet size as well as the field distribution pattern (Hills & Gu, 1989).

Little research has been carried out on irrigation nozzle droplet size distributions and even fewer studies have quantitatively assessed the relationship between nozzles size, operating pressure and distribution characteristics. Generally, at the conditions of the experimental tests the typical range of droplet diameters encountered is between 0.3 and 4 mm (Solomon *et al.*, 1985; Keller & Bliesner, 1990).

Droplet size distribution can be investigated by both direct methods (sensitive paper, oil, flour, photography, laser velocity, *etc.*) and indirect ones. Calibrated stain techniques were used by Inoue and Jayasinghe (1962), Inoue (1963) and Seginer (1963). Kohl and De Boer (1983) resorted to the pellet method to measure the size of droplets from irrigation nozzles, while Von Bernuth and Gilley estimated droplet size distributions from radial curves. Spraying Systems Co (1968) presented volume media droplet diameters for their flooding nozzles for various nozzle size and operating pressures. On the whole, complete droplet size distributions for irrigation spray nozzles are relatively rare. Tate and Janssen (1965) and Tate (1968 and 1977) presented a total of three distributions for flooding style spray nozzles while Kohl and De Boer (1983) presented fourteen distributions for different types of nozzles.

Concerning probabilistic models, Mugele and Evans (1951) proposed the upper limit log normal (ULLN) distribution function to describe spray droplet data. The distribution is based on the assumption that the droplet diameter is related to a pseudo one, log-normally distributed. The peculiarity of the model consists in the fact that the ULLN distribution function can refer to either number or volume frequency **(**Goering & Smith, 1976). The same authors found that the distribution fits well the drop size distributions from a wide variety of agricultural spray nozzles. Bezdek and Solomon (1983) showed good ULLN fits to both sprinkler and spray nozzle drop size data. Solomon *et al.* (1985) developed a regression model to predict ULLN parameters as functions of nozzle style, size and operating pressure.

All these studies share the awareness of the difficulty of being able to comprehend clearly the process of spray evaporation in sprinkler irrigation. The problem is due to the very many parameters that mutually affect each other. To this end Lorenzini (2002) carried out an experimental study (following the relevant standards) in the field on sprinkler irrigation evaporation. This study only treated the influence of the environmental air temperature, keeping all the other variables constant and minimising the experimental error. A single sprinkler was tested in-field and this, obviously, led to higher evaporation with respect to the many adjacent sprinklers. Each irrigation test was performed with sprinklers working in steady-state for a time interval of 360 seconds, and the flow rate delivered by the sprinklers was always equal to 18.15 ls^{-1}. These results are significantly higher compared to those of Thompson *et al.* (1997), but it should be noted that the climatic conditions during the experimental tests of Lorenzini (2002) were far more homogeneous, and therefore more suitable for singling out each parametrical contribution than those considered in the paper quoted above. In fact, the Thompson *et al.* evaporation measurements, each of which was carried out for a whole day, were obviously affected by the usual daily thermal rushes, and are therefore difficult to interpret. The air temperature effect has been proved here to significantly affect sprinkler spray evaporation, something that up to now has generally been neglected.

CONCLUSIONS

Irrigation water that is applied to crops is most effective if that water enters the transpiration stream and contributes directly to the matter accumulation. Unfortunately, some of the irrigation water may be lost by evaporation and never be able for transpiration or direct contribution to yield. Evaluating the losses associated with an overhead sprinkling system is challenging because evaporation can occur from droplet before they reach the canopy, from wet leaves, and wet soils. Therefore, a thorough understanding of the factor affecting spray flow and evaporation losses in sprinkler irrigation systems represents a great help in assessing the performance of the systems and in developing appropriate water conservation strategies. The issue requires a full analytical description of how a droplet exiting from a nozzles reaches a solid surface and entails both experimental and theoretical studies. In the former, it appears to be hard to identify an so to measure, the contribution of each parameter to the final result. In the latter, the non-linear relationships among the variables make it difficult to obtain an exhaustive analytical picture of the process. Usually a distinction was made between evaporation and wind drift and attempts were made to assess these two components separately, but accurate evaluations are difficult to achieve.

Despite these difficulties important statistical relationships and physical-mathematical models, that link spray losses to the factors affecting them, have been proposed.

An important work along the first line is that of Frost and Schwalen (1955), resulting in a monogram relating spray losses to environmental and operational conditions. Later on, Tarjuelo *et al*. (2000), proposed a regression model that proved to be a useful tool to determine irrigation timing and to minimise evaporation and drift losses.

Among the analytical studies, the heat and mass transfer analogy, linked with particle ballistics, offers a well-established approach to assess jet flow and evaporation losses. The procedure describes the event of a droplet travelling from the sprinkler nozzle to the ground as a combination of environmental parameters such as pressure gradient, vapour concentration, air relative humidity, resulting in very elaborate formulae and strongly condition-dependent. The results are in reasonable agreement with experimental data for Reynolds numbers, generally, lower than 1000, that fall , mainly, under the laminar and/or intermediate flow laws. However, this range covers too small an interval of values to be of a general utility in irrigation practice. To narrow this gap, Lorenzini and De Wrachien proposed a model suitable to assess the contribution given to the droplet evaporation by friction force during the aerial flight of the droplet, within the field of the turbulent flow law. This approach has not been found elsewhere, probably because air friction was considered as a factor of minor relevance in affecting spray evaporation.

Notwithstanding all these effects, a full comprehension of sprinkler evaporation losses has not been reached yet. So a deepening of both the theoretical and experimental activities is needed to allow the Scientific Community further steps towards a thorough understanding of the phenomena.

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