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Analytical Study of Wind Influence on In-Flight Sprinkler Droplets

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Abstract. An analytical model to describe the dynamics of in-flight droplets is presented in this paper to augment information on wind influence on travel distance of in-flight sprinkler droplets. The model is ballistic-theory based. It employs a relatively simple, wide-range empirical relationship between drag coefficient and Reynolds' number to replace the several sets of relations for a specified range of Reynolds numbers. The fourth-order Runge-Kutta numerical integration techniques were used to solve the trajectory equations. A modified exponential model for droplet size distribution was used during the simulation. Comparative analysis showed that agreement exists between the predictions of this model and that of earlier models. Droplets with a diameter smaller than 0.1 mm travelled farthest. Within the droplet range of 0.5 mm to 4.5 mm, as droplet diameter increased, travelled distance increased with increasing wind speed. The extent of drift increased sharply within the droplet range of 0.5 mm to 0.05 mm and increased mildly for droplet diameters greater than 0.5 mm. The model also attempts to identify droplets that are likely to contribute to drift loss and those that have a high probability of contributing only to distortion of the distribution pattern.

Keywords: *analytical model; droplet drift; distribution pattern; simulation; sprinkler droplets; traveled distance; wind influence.*

1 Introduction

The influence of wind during sprinkler irrigation pose challenges that need attention especially in this era of water conservation towards a sustainable use of resources. Most sprinklers apply water to the ground by projecting water jets into the air at high velocity, which later fall down as water droplets. Under windy conditions, in-flight sprinkler water droplets may impact the ground or plant canopy, experience droplet evaporation or be wind drifted [1-3].

Sprinkler droplet travel under no-wind condition is undisturbed and thus a characteristic of the sprinkler nozzle for a given operation configuration. If droplets travel beyond their characteristic distances for the same sprinkler

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nozzle and pressure configuration, they are considered as drifted. These drifted droplets contribute to wind distortion of the distribution pattern [3,4].

Several simulation studies have been carried out to model various aspects of wind effect on sprinkler droplets over the years [3,5-9]. Several factors affect the trajectories and losses of in-flight water droplets that complicate adequate description and estimation of wind drift [10-12].

Studies that have simulated droplet drift loss are few. Notable among these are Edling [13]; Seginer, *et al.* [8]; Martin and Newman [4]; Thompson, *et al.* [14]; McLean, *et al.* [15]; Teske, *et al.* [9]. Edling and Chowdhury [16] and Longley [17] presented theoretical models for estimating spray evaporation and wind drift from low-pressure spray sprinklers. Molle, *et al.* [18] also reported on evaporation and wind drift loss during sprinkler irrigation. Lorenzini and Saro [19] studied thermal fluid dynamic modeling of a water droplet evaporating in air by considering wind drift (but with uniform velocity field) by applying the Runge-Kutta integration method.

This paper presents an analytical description of the dynamics of droplets from a single operated irrigation sprinkler to augment the pioneering works of earlier researchers on in-flight sprinkler droplets. Specifically, we seek to simulate the dynamics of wind influence on the travel distance of sprinkler droplets.

2 Materials and Method

2.1 Model of Droplet Motion

Several models have already been developed by researchers that consider a sprinkler as a device emitting numerous droplets with diameter as a function of their travelled distances [5,6,8]. According to ballistic theory, droplets' motions are influenced by the initial velocity vector, the gravitational force, the wind vector and the viscous drag force. Eqs. (1) to (3) were solved to compute the droplet trajectories.

$$\ddot{x} = \frac{d^2x}{dt^2} = \frac{3\bar{\rho}}{4d} C\left(u_f - u\right) w_r \tag{1}$$

$$\ddot{y} = \frac{d^2y}{dt^2} = -\frac{3\bar{\rho}}{4d} C\left(v_f - v\right) w_r \tag{2}$$

$$\ddot{z} = \frac{d^2z}{dt^2} = -\frac{3\bar{\rho}}{4d} C\left(\omega_f\right) w_r - g \tag{3}$$

where x, y and z are the coordinates referring to the ground (with origin at the sprinkler nozzle); d is the droplet diameter (mm); $\bar{\rho}$ is the density ratio of air and water respectively; t is time (s), and g is acceleration due to gravity. C is the air drag coefficient of the droplet moving at the speed w_r.

$$w_r = \sqrt{[(u_f - u)^2 + (v_f - v)^2 + \omega_f^2]} \tag{4}$$

u and v are the horizontal and vertical components of the droplet velocity, respectively; u_f , v_f and ω_f are the x, y and z components of the wind velocity respectively. Since the logarithmic profile of wind speed is generally considered to be a more reliable estimator of the actual field conditions, the average wind speed (U_r) at height r (cm) above the ground was calculated for all conditions as:

$$U_r = U_m \frac{\ln[(r-D)/Z_0]}{\ln[(m-D)/Z_0]} \tag{5}$$

U_m = wind speed (m/s) measured at reference height m (cm) above the ground. D and Z_O are roughness height (cm) and roughness parameter (cm) respectively, both are functions of crop height h (cm), given by:

$$\log D = 0.997 log h - 0.1536 \qquad \log Z_O = 0.997 \log h - 0.883 \tag{6}$$

2.2 Boundary and Initial Conditions

Height of sprinkler nozzle: 1.2 m (most sprinklers mounted on risers are within the range of 0.8 to 1.5 m); droplet diameter range considered: 0 < droplet diameter (mm) < 5; wind speeds: 0, 2.5, 3.5 and 4.5ms^{-1}; operating pressure: 250,300,350 kPa.

The fourth-order Runge-Kutta numerical integration techniques were used to solve equation (1), (2) and (3) for droplet movement with the specification of initial conditions as follows:

$x(t = 0) = 0;\dot{x}(t = 0) = v_{0,x}$; $y(t = 0) = 1.2\, m$ (height from ground to sprinkler nozzle = 1.2 m); $\dot{y}(t = 0) = v_{0,y}$. $v_{0,x} = v_0 \cos\alpha$; $v_{0,y} = v_0 \sin\alpha$; α is the inclination of the sprinkler nozzle to the horizontal. The velocity of the sprinkler jet exiting from the nozzle was calculated as:

$$v_0 = \mathrm{C_d}(2gH)^{0.5} \tag{7}$$

where $H(m)$ is the operating pressure head at the nozzle and $\mathrm{C_d}$ is the discharge coefficient, equal to 0.98.

By setting $z = 0$ (soil surface) or catch can elevation, each trajectory solution is constituted by the x and y coordinates. Two categories of simulations were conducted: no-wind and in-wind conditions. Droplet travel distances were simulated for both under-wind and no-wind conditions. The horizontal distance between the nozzle exit and the droplet landing point was simulated as the droplet travel distance.

2.3 Empirical Model of the Drag Coefficient

To determine the trajectory of the droplet projectiles in the air, a relatively simple, wide-range empirical relationship between the drag coefficient (C) and the Reynolds' number (R_e), proposed by Holterman [20], was employed to replace the several sets of relations for a specified range of Reynolds numbers, as displayed in Eqs. (7) and (8).

$$C = \left[\left(\frac{a}{R_e}\right)^c + b^c\right]^{1/c} \tag{8}$$

$$R_e = \frac{vd}{\vartheta} \tag{9}$$

where $a = 24$; $b = 0.32$; $c = 0.52$; d=droplet diameter (m), v=velocity (ms^{-1}) and ϑ=the kinematic viscosity of the air (m^2s^{-1}). The adopted relationship compares very well with the well-known set of relations by Fukui, *et al.* [5]. The model is applicable not only to the turbulent-flow regime, but also to the Stokes regime. However, it shows some deviation from the experimental data for $R_e > 10^4$.

2.4 Estimation of Droplet Size Distribution

Several mathematical models and data have been published for drop size distribution for distinct types of sprinkler devices using different methods and operated at varying pressures, nozzle sizes and heights [21-25]. In this study, the simple exponential model used by Li, *et al.* [25], which was later modified by Kincaid, *et al.* [24], was used. The exponential model is given by Eq. (10).

$$P_v = 100\left\{1 - exp\left[-0.693(\frac{d}{d_{50}})^n\right]\right\} \tag{10}$$

Where P_v is the percentage (%) of the total drops that are smaller than d; d is the drop diameter (mm); d_{50} is the volume mean drop diameter (mm); n is the dimensionless exponent. Kincaid, *et al.* [24] found out that Eq. (10) together with the following suggested adjustment factors gave reasonable predictions that cater for smaller diameter droplets.

$$d_{50} = a_d + b_d R \text{ and } n = a_n + b_n R \tag{11}$$

The regression coefficients used for estimating the drop size distribution parameters for the impact sprinkler with small round nozzle (3 mm) are: a_d = 0.31; b_d = 11, 900; a_n = 2.04; b_n = -1,500; R is the ratio of the nozzle diameter to the pressure at the base of the sprinkler device. Sprinkler droplets were assumed to be spherical in shape (this is consistent with the photographic studies by Okaruma and Nakanishi [26]). It was also assumed that the volume of the droplet is invariant during its flight from the nozzle to the ground. The droplet sizes distributions derived from Eqs. (10) and (11) that were used in the analysis are shown in Figure 1.

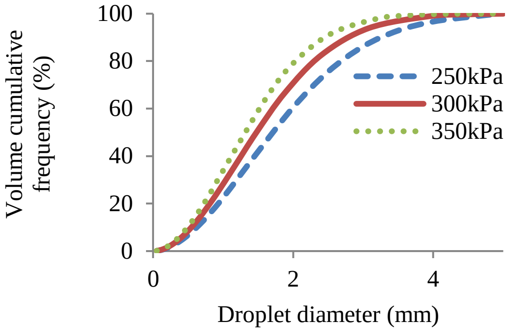

Figure 1 Droplet size distribution derived and used for model analysis.

3 Results and Discussion

3.1 Comparative Analysis of Models

A comparative analysis of droplet travel distance by the models of Molle, *et al.* [18], Fukui, *et al*. [5], von Bernuth and Gilley [26] and our model are presented in Figure 2. Agreement exists between our model and that of Molle, *et al.* [18] for droplets with diameters greater than 2.5 mm, while some differences exist for droplets with diameters smaller than 2.5 mm.

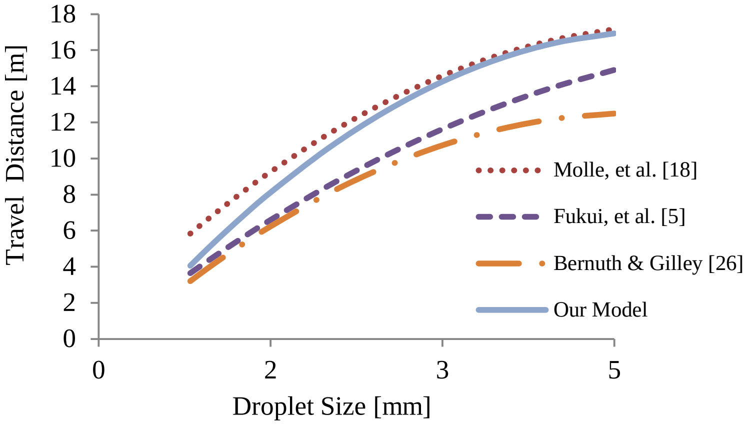

Figure 2 Comparison between other simulated travel distances.

Even though similarity exists in terms of the shape of the trajectory, the travel distances simulated by our model are longer than those of Fukui *et al.* [5] and von Bernuth & Gilley [27] but shorter than those of Molle *et al.* [18]. The disparities can be attributed mainly to differences in the operating parameters and assumptions used in the simulation.

3.2 Effect of Wind Speed on Droplet Travel Distance

Simulated droplet travel distances from the sprinkler for three wind speeds with downwind direction, and zero-wind condition at constant pressure (300 kPa) are compared in Figure 3. Droplets with diameters smaller than 0.1 mm travelled farthest, travelling beyond 24 m from the nozzle exit. This is in agreement with the work of Molle, *et al.* [18]. Wind increased droplet travel distance downwind. Within the range of 0.5 mm to 4.5 mm, as droplet size and wind speed increased, travelled distance also increased. The extent of drift is defined here as the difference between the droplet travel distance under no-wind and in-wind situations for the same sprinkler nozzle-pressure configuration. The extent of drift increased sharply within the droplet range of 0.5 mm to 0.05 mm and then increased mildly for droplets diameters greater than 0.5 mm (Figure 4).

From Figure 1 (for 300 kPa), droplets with a mean diameter larger than 4.0 mm, representing a frequency of 0.92% of the total number of droplets, and droplets with a mean diameter smaller than 0.2 mm, representing a frequency of less than 3%, traveled beyond the wetted radius (Figure 3). Such categories of droplets, apart from contributing to distortion of the distribution pattern, also have a higher probability of contributing to wind drift for sprinklers that are located at the periphery of the irrigated field.

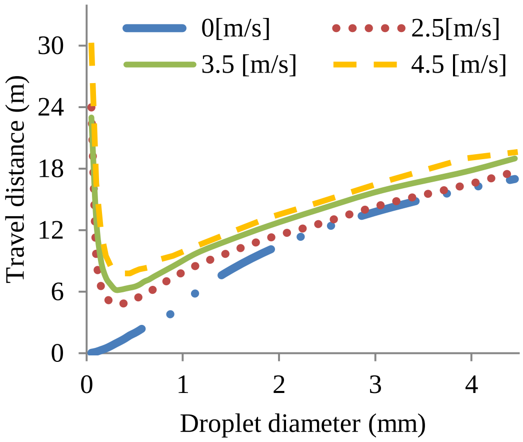

Figure 3 Comparison of droplet travel distance between no-wind and in-wind conditions at constant pressure (300 kPa).

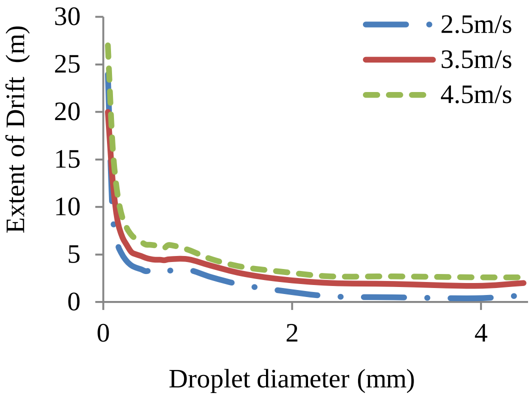

Figure 4 Comparison of extent of drift (m) as a function of droplet size (mm) at three wind speeds at constant pressure (300 kPa).

The remaining droplets are more likely to contribute to distortion of the distribution pattern. Even though larger droplets (with diameter > 4 mm) represent a small percentage of the number of droplets in the droplet distributions considered (Figure 1) due to their high volume per droplet; if they are wind-drifted they will constitute a high percentage loss.

For example, at a constant operating pressure of 300 kPa, at wind speeds of 3.5 m/s and 4.5 m/s, 20% and 32% of the total volume travelled beyond 17 m (the wetted radius), respectively. Of these percentages, 70-90% were larger drops (> 3.9 mm) representing 3.6% and 6.3% of the total number of drops in the distribution, respectively. Hence the percentage of large droplets in the distribution spectrum should not only be of interest for predicting water droplet impact [24], but can also be critical for estimating wind drift losses as well. The above observation is particularly important as it partially identifies droplets that are likely to contribute to drift losses and those that have a high probability of contributing only to distortion of the distribution pattern.

4 Conclusion

The paper presented an analytical model to describe the dynamics of wind effect on in-flight sprinkler droplets. A comparative analysis showed that agreement exists between the predictions of this model and those of earlier models. Droplets with a diameter smaller than 0.1 mm travelled farthest. Within the droplet range of 0.5 mm to 4.5 mm, as the droplet diameter increased travelled distance increased with increasing wind speed. The extent of drift increased sharply within the droplet range of 0.2 mm to 0.05 mm and then increased gently for droplet diameters greater than 0.5 mm. The model also identified droplets within the mean diameter ranges of 0.05 to 0.1 mm and greater than 3.9 mm as likely to contribute to both distortion of the distribution pattern as well as wind drift, especially for sprinklers located at the periphery of the irrigated area when wind speeds are greater than or equal to 3.5m/s.

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