LABORATORY SIMULATION OF EVAPORATION OF WATER DROPLETS ON ARTIFICIAL SOYBEAN LEAVES

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ABSTRACT


The evaporation from water droplets on artificial soybean leaves was modelled using an energy balance. Observations showed that while droplets were hemispherical initially, they then flattened keeping the base area virtually constant. These observations led to modelling the process as evaporation from a vertical right-circular cylinder which gave excellent agreement with indoor data.

INTRODUCTION

A knowledge of the evaporation rate of water droplets on leaves is essential in epidemiology because wetness duration together with leaf temperature are the factors often controlling spore germination and growth. Crowe et al. (1961) had only limited success in predicting wetness duration using regression analyses on weather station windspeed, radiation and temperature data. Shuttleworth (1975a, b, c, d) adopted the more rigorous Penman-Monteith approach in which he incorporated a surface resistance that accounted for partially-wet canopies. His objective was to model the total amount of intercepted water evaporated from a whole canopy. However, these approaches do not address the wetness duration on those specific shaded leaves where wetness duration after rain is longest and therefore where infection is most likely to begin. Pedro and Gillespie (1981) developed a dew model for individual leaves, assuming that moisture is deposited as a film over the leaf surface. Leclerc (1982) used Pedro's model to consider the evaporation of rainwater from the upper side of a shaded leaf. Modifications included the introduction of a stomatal resistance on the lower leaf surface, zero long wave exchange between the leaf and its surroundings due to shading, and the introduction of a transfer enhancement factor of 1.5 for daytime turbulence levels (Pearman et al., 1972). The mass of water was measured after rain and irrigation, and the model, which assumed that moisture is spread over the leaf as a uniform film, was

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tested. Evaporation rates were overestimated by a factor of three. It was suspected that the uneven distribution of water on the surface was the cause.

Leclerc (1982) recognized that the evaporation of rain droplets from an otherwise dry leaf surface was significantly different from drying of a uniformly wet surface, and she developed a new model. Even though local transfer coefficients for flat plates are known to decrease rapidly with increasing distance from the leading edge, this does not hold for cases where diffusion occurs locally on a flat plate. This is attributed to the fact that on a uniformly wet plate, the boundary layer builds up and becomes progressively wetter and colder along the plate. However, on a dry plate with wet spots the boundary layer does not become wetter and colder with distance from the leading edge. Moreover, hemispherical drops on a few cm width plate protrude outside the boundary layer for much of their lifetime. Because transfer coefficients describing the rate of diffusion from hemispheres on flat plates were not found in the literature, it was assumed that the evaporation from these hemispheres would be similar to the evaporation from spheres in a free airstream. This model overestimated the time required for drops to evaporate even though free airstream transfer coefficients had been used. Further investigation resulted in the observation that while raindrops on soybeans typically have an initially hemispherical shape, they quickly become flatter on top and more like short cylinders as evaporation proceeds, both indoors and outdoors. Further evaporation results in disk-shaped wet spots with radii very similar to those of the original hemispheres. Thus a model which unrealistically assumes that the shape of the evaporating droplet remains hemispherical, increasingly underestimates the exposed wet-surface area and the evaporation rate as the remaining volume of water decreases. The model presented below assumes cylindrically-shaped drops that decrease in height to become wet disks as evaporation proceeds. Therefore in the light in which the droplet shape changed with time, it was believed that modelling the drop as a short vertical cylinder represented the actual evaporation without however making any extrapolation to field conditions.

METHODS AND TECHNIQUES

Droplets placed on an artificial leaf cut from cardboard and covered with a wax film (Parafilm “M”, American Can. Co., Greenwich, CT) were used for controlled indoor studies since these exhibited similar behaviour to droplets on soybean leaves. It was noticed that the initially hemispherical droplet shape (Fig. 1) was soon lost after evaporation began, and that the elevation of a drop was reduced while the radius of its base (radius of the wet leaf area) remained nearly equal to that of the original hemispherical drop. The droplets were set at about one centimeter from the leading edge so that the transfer coefficients would not differ due to their position on the
leaf and their initial diameters were measured with a micrometer (Mitotoyo 505-626, Tokyo, Japan). The leaf was secured tightly to prevent fluttering and windspeeds varying from 100 to 300 cm s\(^{-1}\) were simulated with two fans (Torcan, Concord, Ontario; Sheldons Eng., Cambridge, Ontario). Windspeed was measured using a heated thermopile (Hastings-Raydist, model LAM-5K, Hampton, Virginia, USA). Air temperature and vapour pressure were measured using a psychrometer (Casella, London, England). Net radiation exchange was assumed to be negligible. Observed periods of drying were timed and compared with predictions from the model described below.

**THE MODEL**

The basic energy balance equation for a drop evaporating is:

\[
H = LE 
\]  

where \(H\) is the sensible heat flux in watts and \(LE\) is the latent heat of vaporization, also in watts. Net radiation is assumed to be negligible in the present experiment but it can be easily included in the analysis. However, since the intent is eventually to model the most slowly evaporating droplets in a canopy, this might be an appropriate assumption under field conditions.

The heat flux toward the drop modelled as a short cylinder is given by

\[
H = (\rho C_p h)(T_s - T_w)A_t 
\]  

where \(\rho C_p\) is the heat capacity of the air, \(h\) the heat transfer coefficient,
\((T_a - T_w)\) is the temperature difference between the air and the water and \(A_t\) is the total surface area of the cylinder of height \(C_h\) including both ends since part of the heat flux comes through the leaf.

\[ A_t = 2\pi r^2 + 2\pi rh \]  

(3)

In low-light conditions the leaf is assumed to be at \(T_a\) except for the disc under the droplet which is assumed to be at \(T_w\). The transfer coefficient is given by

\[ h = NuD_H/2r \]  

(4)

where \(D_H\) is the thermal diffusivity of the air and \(r\) the radius of the droplet.

The Nusselt number used for a cylinder was

\[ Nu = 0.62Re^{0.47} \]

whereas at the end of the evaporation, when the cylinder decreases to become a flat disc, the Nusselt number can be expressed as (Bird, et al., 1960)

\[ Nu = 0.60Re^{0.5} \]  

(5)

However, because of the similarity between the absolute values of those Nusselt numbers (about 3% error for \(400 < Re < 4000\)), the correlation for a flat plate was used instead of the correlation for a cylinder throughout the entire analysis. \(LE\) is given by

\[ LE = LMhA(1.07)(e_{sw} - e_a)/RT \]  

(6)

where \(L\) is the latent heat of vaporization, \(e_{sw}\) and \(e_{sa}\) are the saturated vapour pressures at the water temperature and air temperature, respectively; \(e_a\) is the ambient vapour pressure, \(R\) the universal gas constant, \(T\) the mean temperature between the air and the droplet, \(M\) the molecular weight of water, \(A\) the area of the evaporating surface, and 1.07 the ratio of the diffusion coefficient for water vapour to the thermal diffusivity of air.

The vapour pressure difference \((e_{sw} - e_a)\) is calculated using the slope of the saturation vapour pressure curve

\[ e_{sw} - e_a = e_{sw} - e_{sa} + e_{sa} - e_a = s(T_w - T_a) + e_{sa} - e_a \]  

(7)

Equations (4) and (5) may be substituted for \(h\) in eqs. 2 and 6 and eq. 7 may also be used in eq. 6. This leaves three equations 1, 2 and 6 in the three unknowns \(H\), \(LE\) and \((T_a - T_w)\). \(LE\) may then be obtained provided \(T_a\), \(e_a\), \(r\) are measured, since \(A\) and \(A_t\) may be calculated from \(C_h\) as described below.

To start the evaporation simulation, the cylinder is constrained to the same evaporation rate as the original hemispherical drop by setting the two surface areas equal and solving for the initial height \(C_{hi}\). The evaporation area for a right-circular cylinder on a leaf, unlike that for the heat flux, is made of the top and the walls of the cylinder.
The hemispherical drop has the same radius as the cylinder and an evaporating surface area of

\[ A_{\text{hsp}} = 2\pi r^2 \]  

(9)

Equating (8) and (9) yields, for time \( t = 0 \)

\[ C_{\text{hi}} = r/2 \]  

(10)

and initial values of \( A_t \) and \( A \) may be found from (3) and (8). Note that the cylinder also has the same surface area as the real droplet at the end of the simulation when both have collapsed to a wet disc.

Using \( C_{\text{hi}} \), \( LE \) is initially calculated for a time period of 1 min and converted to an equivalent volume of evaporated water, \( \Delta V \). Then the new droplet volume \( V \) is

\[ V = V_0 - \Delta V \]  

(11)

where \( V_0 \) is the original volume of water, \( (2/3)\pi r^3 \). A new value of \( C_h \) is then found from

\[ C_h = (V/V_0)C_{\text{hi}} \]  

(12)

and hence new values of \( A_t \) and \( A \) are available from (3) and (8). The simulation proceeds for another 1 min time step at which time \( V \) is further reduced by the new value of \( \Delta V \), \( C_h \) is recalculated from (12), and so on until \( V = 0 \) and the total time required for the drop to evaporate has been simulated.

A synopsis of the procedure is as follows: (1) \( T_a, e_a, r \) are measured. (2) \( C_{\text{hi}} \) is found from (10), and hence initial values of \( A_t \) and \( A \) from (3) and (8). (3) Evaporation rate is found from simultaneous solution of (1), (2) and (6) after substitution from (4), (5) and (7). (4) Initial water volume is reduced by the evaporation occurring during a 1 min time step in (11). (5) \( C_h, A_t \) and \( A \) are recalculated from (12), (3) and (8). (6) Steps 3 to 5 are repeated until the water volume becomes zero.

RESULTS

Figure 2 and Table I show the predicted versus observed drying time and excellent agreement can be seen. Under our experimental conditions, radial conduction of energy through the “leaf” to the droplet did not appear to be significant. It is apparent that initially hemispherical drops evaporating within 1 cm of the edge on an otherwise dry leaf, without changing radius, may be modelled as slowly shortening cylinders that behave as if the leaf was not present. Further experiments are required with drops at various distances from the leading edge but recent investigations (Leclerc et al., 1985) using an electrochemical technique developed by Schuepp (1972) suggest that
Fig. 2. Predicted drying time versus observed drying time.

TABLE I

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<tr>
<th>Environmental parameters</th>
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<td>Diameter (cm)</td>
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The droplet position has little effect. If this proves true, especially in tests out-of-doors where turbulence levels are higher than indoors and may further contribute to removing any influence of leaf boundary layers, then an estimate of the longest wetness duration for pest management could simply be based on knowledge of the largest droplet size retained on shaded foliage.

It must be stressed however that the present paper is intended solely to describe the evaporation of a droplet whose shape, hemispherical at first, flattens gradually to become a short vertical cylinder and eventually a disc. The aim of this paper is not to predict the actual evaporation under field conditions.
conditions. Further testing is needed to confirm the validity of the model out-of-doors. It should also be noted that for leaves having different surface characteristics such as hairiness, wax structures or veins, the drops formed can have very different shapes varying from nearly perfect spheres on a corn husk to a thin film on white bean leaves. To describe the drying rate in these cases, it would be necessary to modify our equations to fit spherical or disc-shaped droplets. However, it is likely that drying models including the three cases of hemispheres, spheres and discs would describe droplet wetness duration for many economically important crops on which disease management might be practised.

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REFERENCES