water

Supplementary Material

Develop a Smart Microclimate Control System for Greenhouses through System Dynamics and Machine Learning Techniques

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Formulation of the physically based estimation model

A. Formulating greenhouse internal ***relative humidity***

The physically based model of internal relative humidity is constructed by the equations of the conservation of mass and the conservation of energy, as shown in Equation (S1):

$$\frac{dH}{dt} \times V_{GH} \times D_{air} = \beta_{i,t} \times Water_{i,t} + Vent_{i,t} \times D_{air} \times \left(H_{o,t} - H_{i,t}\right) \quad (S1)$$

where $\frac{dH}{dt}$ is the change rate of the indoor absolute humidity in a time period (kg/m^3 hr); $\beta_{i,t}$ is the spray efficiency (%) at t; $Water_{i,t}$ denotes the amount of spray (kg) at t; $Vent_{i,}$ denotes the indoor ventilation (kg /hr) at t; $H_{i,t}$ and $H_{o,t}$ denote the internal and external absolute humidities (kg/m^3) at t, respectively; V_{GH} denotes the total capacity of greenhouse (m^3); and D_{air} denotes the air density (1.2 kg/m^3).

To estimate the internal absolute humidity at t+1 requires calculating internal and external saturated vapor pressures at t, defined in Equations 2 and 3, respectively:

$$esi_{i,t} = 0.6178 \times e^{\frac{17.2694 \times T_{i,t}}{(T_{i,t}+237.3)}} \quad (S2)$$

where $esi_{i,t}$ denotes the internal saturated vapor pressure (kpa) at t and $T_{i,t}$ denotes the indoor temperature (℃) at t;

$$esi_{o,t} = 0.6178 \times e^{\frac{17.2694 \times T_{o,t}}{(T_{o,t}+237.3)}} \quad (S3)$$

where $esi_{o,t}$ denotes the external saturated vapor pressure (kpa) at t and $T_{o,t}$ denotes the external temperature (℃) at t.

Internal and external absolute humidities at t are defined in Equations 4 and 5, respectively:

$$H_{i,t} = 0.62198 \times \frac{RH_{i,t} \times esi_{i,t}}{(P_{atm} - RH_{i,t} \times esi_{i,t})} \quad (S4)$$

where $H_{i,t}$ denotes the indoor absolute humidity (kg/m^3) at t, $RH_{i,t}$ denotes the indoor relative humidity (%) at t, $esi_{i,t}$ denotes the indoor saturated vapor pressure (kpa)at t, and P_{atm} denotes the atmospheric pressure (101 kpa);

$$H_{o,t} = 0.62198 \times \frac{RH_{o,t} \times esi_{o,t}}{(P_{atm} - RH_{o,t} \times esi_{o,t})} \quad (S5)$$

where $H_{o,t}$ denotes the external absolute humidity (kg/m^3) at t, $RH_{o,t}$ denotes the external relative humidity (%) at t, $esi_{o,t}$ denotes the external saturated vapor pressure (kpa) at t, and P_{atm} denotes the atmospheric pressure (101 kpa).

In greenhouses, the proportion of evaporation is low under spray conditions. Therefore, it is important to understand spray efficiency when identifying the degree to which the spray evaporates.-According to Bottcher et al. (1991), the relationship between relative humidity and spray efficiency can be expressed by Equation (S6):

$$\beta_{i,t} = 1.1906 - 0.09077 \times RH_{i,t} \quad (S6)$$

where $\beta_{i,t}$ denotes the indoor spray efficiency (%) at t and $RH_{i,t}$ denotes the indoor relative humidity (%) at t.

In addition to absolute humidity and spray efficiency, ventilation is also an essential element to calculate internal relative humidity. The ventilation rate can be obtained from Equation (S7):

$$\text{Vent}_{i,t} = C_{i,t} \times WS_t \times A_{GH} \quad (S7)$$

where $\text{Vent}_{i,t}$ denotes the ventilation rate (m^3/hr) at t, $C_{i,t}$ is the ventilation utilization factor at t, A_{GH} is the ventilation area of greenhouse (m^2), and WS_t denotes the wind speed (m/hr) at t.

We can estimate internal absolute humidity at t+1 based on the internal absolute humidity change rate and internal absolute humidity at t, as shown in Equation (S8):

$$H_{i,t+1} = H_{i,t} + \frac{dH}{dt} \quad (S8)$$

where $H_{i,t+1}$ and $H_{i,t}$ denote the indoor absolute humidity at t+1 and t (kg/m^3), respectively, and $\frac{dH}{dt}$ is the indoor absolute humidity change rate in a time period (kg/m^3 hr).

According to the internal absolute humidity at t+1, the internal partial pressure of water vapor at t+1 can be deduced, as shown in Equation (S9):

$$ei_{i,t+1} = \frac{H_{i,t+1} \times P_{atm}}{H_{i,t+1} + 0.62198} \quad (S9)$$

where $ei_{i,t+1}$ denotes the indoor partial pressure of water vapor (kpa) at t+1, $H_{i,t+1}$ denotes the indoor absolute humidity (kg/m^3) at t+1, and P_{atm} denotes the atmospheric pressure (101 kpa).

The last calculation step of the internal relative humidity at t+1 is shown in Equation (S10), where the internal partial pressure of water vapor at t+1 is divided by the internal saturated vapor pressure at t+1:

$$RH_{i,t+1} = \frac{ei_{i,t+1}}{esi_{i,t+1}} \quad (S10)$$

where $RH_{i,t+1}$ denotes the indoor relative humidity (%) at t+1, $ei_{i,t+1}$dentoes the indoor partial pressure of water vapor (kpa) at t+1, and $esi_{i,t+1}$ denotes the internal saturated vapor pressure (kpa) at t+1.

B. Formulating greenhouse internal temperature

The internal temperature is also constructed by the equations of the conservation of mass and the conservation of energy, as shown in Equation (S11):

$$\frac{dh}{dt} \times D_{air} \times V_{GH} = (h_{i,t} - h_{o,t}) \times Vent_{i,t} + K_{in} \times A_w \times (T_{s,t} - T_{i,t}) + A_f \times K_f \times (T_{i,t} - T_{f,t}) \quad (S11)$$

where $\frac{dh}{dt}$ denotes the indoor change rate of enthalpy in a time period (kj/kg hr); $h_{i,}$ and $h_{o,t}$ denote the indoor and external enthalpies (kj/kg) in the air at t, respectively; $\text{Vent}_{i,t}$ denotes the ventilation rate (m^3/hr) at t; V_{GH} denotes the total capacity of the greenhouse

(m^3); D_{air} denotes the air density (1.2 kg/m^3); K_{in} denotes the indoor coating material's heat convection parameter in the air (6.4 W/m^2℃); A_w denotes the area of coating material (m^2); $T_{s,t}$, $T_{i,t}$, and $T_{f,t}$ denote the indoor temperature (℃) of the coating material, the indoor temperature (℃), and the indoor ground temperature (℃) at t, respectively; A_f denotes the total ground area of the greenhouse (m^2); and K_f denotes the indoor ground-to-air heat convection parameter (4.65 W/m^2℃).

To estimate the internal temperature at t+1, it requires calculating internal and external enthalpies in the air at t, defined in Equations 12 and 13, respectively:

$$h_{i,t} = 1.006 \times T_{i,t} + H_{i,t} \times \left(2501 + 1.085 \times T_{i,t}\right) \quad \text{(S12)}$$

where $h_{i,t}$ denotes the indoor enthalpy in the air (kj/kg) at t, $T_{i,t}$ denotes the indoor temperature (℃) at t, and $H_{i,t}$ denotes the indoor absolute humidity (kg/m^3) at t;

$$h_{o,t} = 1.006 \times T_{o,t} + H_{o,t} \times \left(2501 + 1.085 \times T_{o,t}\right) \quad \text{(S13)}$$

where $h_{o,t}$ denotes the external enthalpy in the air (kj/kg) at t, $T_{o,t}$ denotes the external temperature (℃) at t, and $H_{o,t}$ denotes the external absolute humidity (kg/m^3) at t.

After obtaining the internal and external enthalpies in the air, the heat conduction equation of the coating material can be used to calculate the internal temperature of the coating material at t using Equations (S14) and (S15):

$$T_{s,t} = T_{o,t} + a \times \left(\frac{Rn_{o,t}}{K_{out}}\right) \quad \text{(S14)}$$

where $T_{s,t}$ denotes the internal temperature of the coating material at t (℃), a is the solar absorption rate on the surface of material (0.65 %), $T_{o,t}$ denotes the external temperature (℃) at t, $Rn_{o,t}$ denotes the external solar radiation (W/m^2) at t, and K_{out} denotes the thermal conductivity on the surface of material (6.3 W/m^2℃):

$$Rn_{o,t} = \left(1 - ref\right) \times par_{o,t} + Rn_{lon} \quad \text{(S15)}$$

where $Rn_{o,t}$ denotes the external solar radiation at t (W/m^2), ref denotes the ground reflectivity (0.2), $par_{o,t}$ denotes the external insolation at t (W/m^2), and Rn_{lon} denotes the atmospheric long-wave radiation (343 W/m^2).

After obtaining the internal temperature of the coating material at t, the internal ground temperature can be calculated based on Equation (S16):

$$T_{f,t} = T_{o,t} + \frac{Rn_{o,t} - B \times \left(T_{o,t} + 273.15\right)^4}{\left(4 \times B \times (T_{o,t} + 273.15)^3\right)} \quad \text{(16)}$$

where $T_{f,t}$ denotes the indoor ground temperature (℃) at t, $T_{o,t}$ denotes the external temperature (℃) at t, $Rn_{o,t}$ denotes the external solar radiation (W/m^2) at t, and B is the Boltzmann constant (5.67×10^{-8} $Wm^{-2}K^{-4}$).

Because this study considers spray to be a means of humidification and cooling, it requires calculating the internal heat moving away due to spray, as shown in Equation (S17) (refers to Fang (1995)):

$$Q_t = \beta_{i,t} \times Water_{i,t} \times H_{fg} \quad \text{(S17)}$$

where Q_t denotes the heat moving away due to spray (kj/hr), $\beta_{i,t}$ denotes the indoor spray efficiency (%) at t, $Water_{i,t}$ denotes the indoor spray amount (kg/hr) at t, and H_{fg} denotes the latent heat of water evaporation (2256.6 kj/kg).

The relationship between internal temperature and heat can be calculated by a specific heat capacity equation engaging the spraying system and the energy conservation formula. Equation (S18) shows how to calculate the internal temperature change:

$$dT = \frac{\frac{dh}{dt} \times V_{GH} \times D_{air} - Q_t}{4.186 \times C_p \times V_{GH} \times D_{air}} \quad \text{(S18)}$$

where dT denotes the indoor temperature change in a time period (℃/hr), $\frac{dh}{dt}$ denotes the indoor change rate of enthalpy in a time period (kj/kg hr), V_{GH} denotes the total capacity of the greenhouse (m^3), D_{air} denotes the air density (1.2 kg/m^3), Q_t denotes the heat moving away due to spray (kj/hr), and C_p denotes the specific heat of air (1.0052 kj/kg ℃).

Finally, the internal temperature at t+1 can be obtained by Equation (S19):

$$T_{i,t+1} = T_{i,t} + dT \quad \text{(S19)}$$

where $T_{i,t+1}$ and $T_{i,t}$ denote the indoor temperature (℃) at t+1 and t, respectively, and dT denotes the indoor temperature change in a time period (℃/hr).