Setpoint decision support strategy and adaptive hybrid control of greenhouse climate: a simulation study

——Supplementary Material

This is the supplementary material to the paper entitled "Setpoint decision support strategy and adaptive hybrid control of the greenhouse climate: a simulation study". It mainly presents the details of the calculations of the heat and mass exchanges between the objects in the greenhouse, and provides some fixed model parameters of the greenhouse climate model.

1. Calculation of heat and mass exchange

1.1. air flux of ventilation

In the considered greenhouse climate model, the natural ventilation rate through roof and sidewall windows can be described respectively as follow [1]:

$$\phi'_{ventroof}=\frac{u_{roof}A_{roof}C_d}{2A_g}\sqrt{\frac{gh_{vent}}{2}\frac{T_{top}-T_{out}}{\overline{T}+273.15}+C_wV_{wind}^2}\qquad [\mathrm{m^3\ m^{-2}\cdot s^{-1}}](1)$$

$$\phi'_{ventside}=\frac{u_{side}A_{side}C_d\sqrt{C_w}V_{wind}}{2A_g}\qquad [\mathrm{m^3\ m^{-2}\cdot s^{-1}}]\ (2)$$

where $\overline{T}=0.5(T_{top}+T_{out})$.

De Zwart presented a method to calculate the air flux between the air below and above thermal screen [2], which is given by:

$$\phi_{ThScr}=u_{scr}K_{ThScr}\left|T_{air}-T_{top}\right|^{0.66}+0.2(1-u_{scr})\qquad [\mathrm{m^3\ m^{-2}\cdot s^{-1}}]\ (3)$$

where K_{ThScr} ($\mathrm{m^3 m^{-2}\cdot K^{-0.66}\cdot s^{-1}}$)) is the screen flux coefficient.

1.2. Crop Transpiration

The humidity inside the greenhouse is impacted significantly by the crop transpiration. Hence, it is important to accurately calculate the transpiration rate for the greenhouse humidity simulation. Generally, the crop transpiration depends on the canopy temperature, the CO_2 concentration, the vapor pressure deficit and the solar radiation above the canopy. Stanghellini proposed a mechanism model to describe the vapor exchange between the air and the canopy [3], which is expressed as:

$$E=\frac{2\rho_{air}C_{p,air}LAI}{\lambda\gamma(r_b+r_s)}(VP_{can}-VP_{air})\qquad [\mathrm{kg\ m^{-2}\cdot s^{-1}}](4)$$

where r_b ($\mathrm{s\ m^{-1}}$) is the boundary layer resistance of the canopy for the vapor transport, and is considered as a constant. In addition, the stomatal resistance of the canopy for vapor transport r_s is another important parameter, which usually depends on the canopy temperature, global radiation and CO_2 concentration, and can be calculated by:

$$r_s=r_{s,\min}f_1\left(R_{can}\right)\cdot f_2(CO_{2,air})\cdot f_3(VP_{can}-VP_{air})\qquad (5)$$

where

$$f_1\left(R_{can}\right)=\frac{R_{can}+c_1}{R_{can}+c_2}$$

$$f_2(CO_{2,air})=1+c_3(CO_{2,air}-200)^2$$

$$f_3(VP_{can}-VP_{air})=1+c_4(VP_{can}-VP_{air})$$

and $c_1\sim c_4$ are the model parameters. The canopy saturation vapor pressure VP_{can} (Pa) can be calculated by [4]

$$VP_{can}=2.229\times10^{11}e^{-\frac{5385}{T_{can}+273.15}},\qquad (6)$$

and the air vapor pressure VP_{air} can be calculated by:

$$VP_{air}=\frac{w_{air}\cdot R\cdot(T_{air}+273.15)}{M_{\mathrm{H_2O}}}\times10^{-3},\qquad (7)$$

1.3. Crop Photosynthesis and Respiration

Although there are many photosynthesis rate models, a mechanism model proposed by Farquhar [5] is used in the greenhouse climate model due to its good simulation performance. It can be described by

$$P_g = \frac{J(CO_{2,stom} - \Gamma)}{4(CO_{2,stom} + 2\Gamma)} \qquad [\text{umol m}^{-2}\cdot\text{s}^{-1}] \quad (8)$$

where $\Gamma = c_\Gamma T_{can}$ (umol mol^{-1}) is the compensation point of the CO2 concentration, $CO_{2,stom}$ (umol mol^{-1}) is the CO_2 concentration in the stomata, and J is the electron transport rate, which can be calculated by:

$$J = \frac{J^{POT} + \alpha PAR_{can} - \sqrt{(J^{POT} + \alpha PAR_{can}) - 4\Theta \cdot J^{POT} \cdot \alpha PAR_{can}}}{2\Theta} \qquad [\text{umol m}^{-2}\cdot\text{s}^{-1}] \quad (9)$$

where α is the conversion factor from photons to electrons, PAR_{can} is the photosynthetic active radiation(PAR) absorbed by the canopy, Θ is the degree of the curvature of the electron transport rate, and is usually a constant. The potential rate of electron transport J^{POT} is impacted by the canopy temperature and leaf area index (LAI), and can be calculated by

$$J^{POT} = J^{MAX}_{25,can} \cdot e^{E_j \frac{T_{can,K} - T_{25,K}}{R \cdot T_{can,K} \cdot T_{25,K}}} \cdot \frac{1 + e^{\frac{S \cdot T_{25,K}}{R \cdot T_{25,K}}}}{1 + e^{\frac{S \cdot T_{can,K} - H}{R \cdot T_{can,K}}}} \qquad [\text{umol m}^{-2}\cdot\text{s}^{-1}] \quad (10)$$

The activation energy E_j for J^{POT} is usually a constant, the absolute canopy temperature $T_{can,K}$ and reference temperature at 25 ^{o}C $T_{25,K}$ can be calculated using the formula $T_{c,K} = T_c + 273.15$. R is the molar gas constant, S is the entropy term and H is the deactivation energy. The maximum rate of electron transport at 25°C for the canopy $J^{MAX}_{25,can}$ usually depends on LAI and the maximum rate of electron transport for the leaf at 25°C $J^{MAX}_{25,Leaf}$, which can be described by

$$J^{MAX}_{25,can} = LAI \cdot J^{MAX}_{25,Leaf} \qquad [\text{umol m}^{-2}\cdot\text{s}^{-1}]$$

The stomatal CO_2 concentration can be calculated by:

$$CO_{2,stom} = \eta_{CO_2 stom} CO_{2,air} \quad (11)$$

As stated in [3], the photosynthesis active radiation absorbed by the canopy PAR_{can} includes two parts. One is from the PAR above the canopy PAR_{ghcan}, the other is from the PAR reflected by the greenhouse floor PAR_{flrcan}. They are described as follow:

$$PAR_{ghcan} = 0.5\eta_{\text{cov}} I_{glob}(1 - e^{-K_{can} \cdot LAI}) \quad (12)$$

$$PAR_{flrcan} = \rho_{flr} PAR_{gh} e^{-K_{can} \cdot LAI} \cdot (1 - e^{-K_{can} \cdot LAI}) \quad (13)$$

where η_{cov} is the light transmission coefficient of the cover, ρ_{flr} the reflection coefficient of the greenhouse floor, and K_{can} is the extinction coefficient of the canopy. Although these parameters usually depend on the properties of the materials and crops, they are fixed as constants in the proposed model. Thus, PAR_{can} can be calculated by $PAR_{can} = PAR_{ghcan} + PAR_{flrcan}$.

If ignoring photorespiration and growth respiration, then total respiration rate of the canopy can be equal to the maintenance respiration. According to Vanthoor's model [3], the canopy maintenance respiration can be described by:

$$R_m = (c_{fruit} DM_{fruit} + c_{stem} DM_{stem} + c_{leaf} DM_{leaf}) Q_{10}^{0.1(T_{can} - 25)} \qquad [\text{umol m}^{-2}\cdot\text{s}^{-1}] \quad (14)$$

where DM_{fruit}, DM_{stem} and DM_{leaf} are the dry matters of the fruit, the stem and the leaf, respectively, and c_{fruit}, c_{stem} and c_{leaf} are their maintenance respiration coefficients.

1.4. Condensation on inner surface of cover

The condensation on the cover depends on the vapor pressure deficit between the cover and air, and can be calculated by:

$$M_{cond} = \begin{cases} 0 & VP_{air} < VP_{\text{cov}} \\ 6.4 \times 10^{-6} K_r (VP_{air} - VP_{\text{cov}}) & VP_{air} \geq VP_{\text{cov}} \end{cases} \quad (15)$$

where VP_{cov} (Pa) is the saturation vapor pressure of the inner surface, and is calculated by

$$VP_{\text{cov}} = 2.229 \times 10^{11} e^{-\frac{5385}{T_{\text{cov}} + 273.15}}, \quad (16)$$

1.5. Estimations of the temperature of the soil, top air, Canopy and Cover

For saving several state variables of the greenhouse climate model, some environmental variables such as the top humidity and CO2 concentration, the temperature of canopy, soil, top air and cover are considered as the time-variant parameters instead of the system state variables, but they must still be evaluated to calculate the heat and mass exchanges.

Although the crop canopy temperature is usually close to the air temperature, there is still big temperature difference in some cases, and the heat capacity of the canopy greatly impacts the greenhouse climate. Therefore, the canopy temperature should be estimated accurately. To estimate the canopy temperature, Kristof proposed an automated leaf temperature monitoring method [6], which is given by:

$$T_{can} = T_{air} + \frac{r_H \cdot \gamma \cdot r_v}{\rho_{air} C_{p,air} \cdot (\gamma \cdot r_v + s \cdot r_H)} R_{can} - \frac{r_H \cdot VPD_{air}}{\gamma \cdot r_v + s \cdot r_H} \tag{17}$$

where $VPD_{air} = VP_{can} - VP_{air}$ is the vapor pressure deficit between the canopy and the air, s (Pa/K) is the slope of the curve relating saturation vapor pressure to the air temperature, and is usually set as 145 at 20 ^{o}C, r_H (s m^{-1}) is the total resistance to the heat transfer between the canopy and the air, which can be calculated by

$$r_H = \frac{\alpha_m}{\beta_m D^{-0.5} v^{0.5} + D^{-0.25} \left| T_{can} - T_{air} \right|^{0.25}} \tag{18}$$

where $\alpha_m \in [330, 670]$, $\beta_m \in [2.2, 7.6]$ are the empirical parameters, D (m) is the characteristic dimension of the leaf, and for tomato leave, the value of this parameter is usually in the interval $[0.05, 0.15]$ (m), v (m s^{-1}) is the air velocity over the leaf. In fact, since v is usually difficult to measure, it is reasonable to set it as a small constant. The total resistance to water vapor transfer r_v (s m^{-1}) can be estimated by r_H, i.e., $r_v = 0.92 r_H$.

According to Kristof's study, r_H can be calculated by:

$$r_H = \frac{\alpha_f}{D^{-0.5} v^{0.5}} \tag{19}$$

where $\alpha_f = 150$ is an empirical parameter. The calculation flow chart is shown in Fig. S1

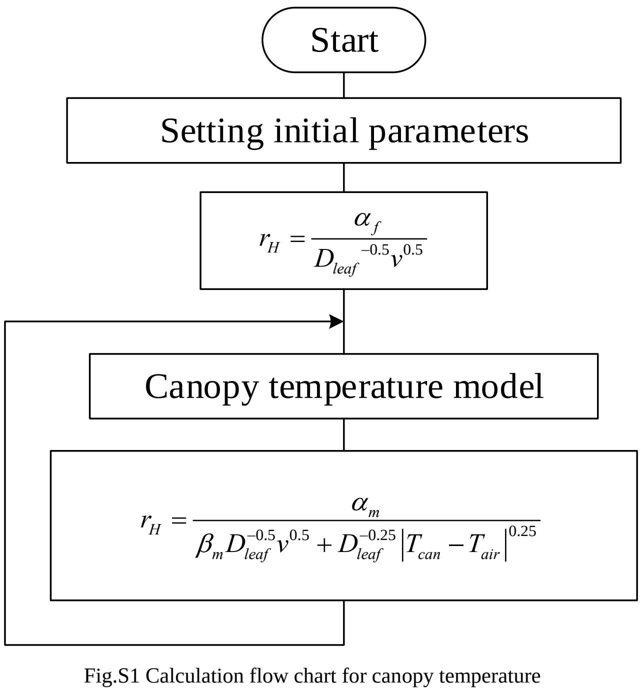

Fig.S1 Calculation flow chart for canopy temperature

The temperature, humidity and CO_2 concentration of the top air in greenhouse are impacted by the weather and the environmental factors below the thermal screen. They can be calculated in a steady-state way, i.e., we have the following steady-state equations:

$$Q_{air\_top} - Q_{top\_cov} - Q_{roofvent} = 0 \tag{20}$$

$$W_{air\_top} - M_{top\_cov} - W_{roofvent} = 0 \tag{21}$$

$$C_{air\_top} - C_{roofvent} = 0 \tag{22}$$

where Q_{air_top} (W m^{-2}) is the heat fluxes between the top air and the air below the thermal screen, Q_{top_cov} (W m^{-2}) is the heat flux from the top air to the cover, and $Q_{roofvent}$ (W m^{-2}) is the heat flux from top greenhouse to outside due to the roof ventilation. W_{air_top} (g m^{-2}), C_{air_top} (umol m^{-2}) are the vapor flux and CO_2 flux from the air below thermal screen to the top air, and M_{top_cov} (g m^{-2}) is the condensation on the roof cover, $W_{roofvent}$ (g m^{-2}), C_{air_top} (umol m^{-2}) are the vapor flux and CO_2 flux through roof windows, respectively. According to the thermodynamic theory, the above three equations can be further rewritten as:

$$\rho_{air}C_{p,air}\phi_{ThScr}(T_{air}-T_{top})-k_r(T_{top}-T_{cov})-\rho_{air}C_{p,air}\phi_{ventroof}(T_{top}-T_{out})=0 \tag{23}$$

$$\phi_{ThScr}(w_{air}-w_{top})-M_{top\_cov}-\phi_{ventroof}(w_{top}-w_{out})=0 \tag{24}$$

$$\phi_{ThScr}(CO_{2,air}-CO_{2,top})-\phi_{ventroof}(CO_{2,top}-CO_{2,out})=0 \tag{25}$$

Where k_r is the heat transfer coefficient between the cover and the top air. From the equations it can be seen that the top temperature and humidity are impacted by the cover temperature. As reported in [7], the cover temperature can be calculated in an algebraic average way, i.e.,:

$$T_{cov}=\frac{1}{\varepsilon}T_{top}+\frac{\varepsilon}{1+\varepsilon}T_{out} \tag{26}$$

where ε is an empirical constant, and it is set as 3 in the simplified greenhouse climate model. Then, the top temperature and CO_2 concentration can be calculated respectively by:

$$T_{top}=\frac{\left(k_r\frac{\varepsilon}{1+\varepsilon}+\rho_{air}C_{p,air}\cdot\phi_{roofvent}\right)T_{out}-\rho_{air}C_{p,air}\cdot\phi_{ThScr}\cdot T_{air}}{\rho_{air}C_{p,air}\cdot\phi_{ThScr}+k_r\frac{1-\varepsilon}{\varepsilon}-\rho_{air}C_{p,air}\cdot\phi_{roofvent}} \tag{27}$$

$$CO_{2,top}=\frac{\phi_{roofvent}CO_{2,out}-\phi_{ThScr}\cdot CO_{2,air}}{\phi_{ThScr}-\phi_{roofvent}} \tag{28}$$

Since M_{top_cov} is impacted by the top humidity, the top humidity can be calculated recursively. If the condensation on the roof cover is ignored, then the top humidity can be calculatedd by:

$$w_{top}=\frac{\phi_{roofvent}w_{out}-\phi_{ThScr}\cdot w_{air}}{\phi_{ThScr}-\phi_{roofvent}} \tag{29}$$

Since the soil temperature changes slower than other environmental variables such as the air temperature and canopy temperature, it is reasonable to estimate the soil temperature using a time series function instead of static function. In this work, the following time series function is used to estimate the soil temperature:

$$T_{soil}(k+1)=T_{soil}(k)+[k_{soil\_air}(T_{air}(k)-T_{flr}(k))+\eta_{soil}I_{glob}-k_d(T_{soil}(k)-T_d)]/Cap_{soil} \tag{30}$$

where k is the discrete time index, k_{soil_air} is the heat transfer coefficient between the air and the soil, k_d (W m^{-2}K^{-1}) is the heat transfer coefficient between the greenhouse soil and the isothermal soil layer, and T_d is the temperature of the isothermal soil layer, which is usually considered as 15^{o}C. The thermal capacity of the soil Cap_{soil} (J Kg^{-1}K^{-1}) can be selected in the interval $[1.2\times10^5, 1.7\times10^5]$. The ratio between the radiation absorbed by the soil and the global radiation depends on LAI, and can be calculated by $\eta_{soil}=(1-\rho_{soil})e^{-K_{can}\cdot LAI}$.

1.6. greenhouse climate control actions

Generally, different actuators have different dynamics, and their effects on the greenhouse climate are different. Therefore, it is difficult to find a common equation to describe the dynamics of the different actuators. In this work, we only consider the direct air heating system, as shown in Fig. S2.

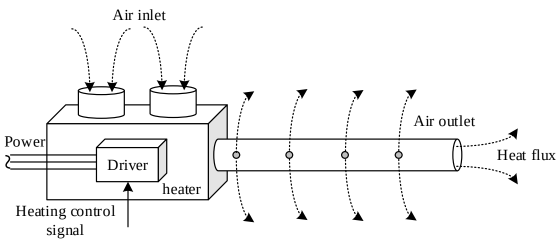

Fig. S2 Direct air heating system

If the dynamics of heater is ignored, then the heat flux from the heater Q_{heat} can be considered as a linear function with respect to the control input, i.e.,

$$Q_{heat}=\frac{u_{heat}}{A_g}\Phi_{N,heat}, \tag{31}$$

where $\Phi_{N,heat}$ (W m^{-2}) is the capacity of heater.

The droplet flux of the fogging system and the CO_2 flux of the CO_2 enrichment system are controlled by the valves, as shown in Fig. S3. Similarly, both fluxes can be calculated respectively by:

$$\phi_{CO_2} = \frac{u_{CO_{2,air}}}{A_g}\Phi_{N,CO_2}, \quad (32)$$

$$\phi_{fog} = \frac{u_{fog}}{A_g}\Phi_{N,fog}, \quad (33)$$

where $\Phi_{N,CO_{2,air}}$ and $\Phi_{N,fog}$ are the capacities of CO_2 enrichment system and fogging system, respectively.

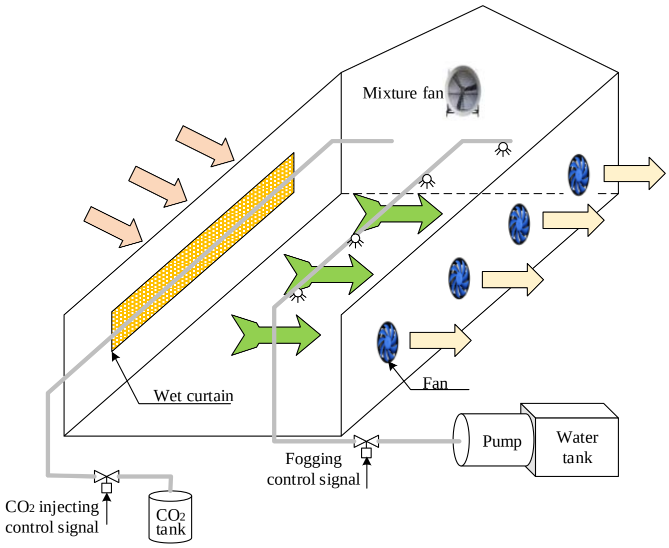

Fig. S3 several control actions in greenhouse

2 Model parameters

The model parameters used in the the greenhouse climate model are listed in Table S1.

Table S1 Fixed model parameters of the gray-box model of the greenhouse climate

symbol	Model parameters	value	unit
H_g	The mean height of the greenhouse	5.1	m
A_g	The area of the greenhouse	7.8×10^2	m^2
A_{cov}	The area of cover	9×10^2	m^2
α_{cov}	The solar radiation absorption coefficient of cover	0.02	-
ρ_{cov}	The solar radiation reflection coefficient of cover	0.13	-
τ_{cov}	The solar radiation transmission coefficient of cover	0.85	-
α_{flr}	The solar radiation absorption coefficient of floor	0.42	-
ρ_{flr}	The solar radiation reflection coefficient of floor	0.58	-
ρ_{air}	Density of air	1.424	Kg m^{-3}
$C_{p,air}$	Specific heat capacity of air	1×10^3	J $K^{-1}kg^{-1}$
C_d	Ventilation discharge coefficient depends on shape	0.65	-
C_w	Ventilation global win pressure coefficient depends on shape	0.09	-
r_b	Boundary layer resistance of canopy	275	s m^{-1}
$r_{s,min}$	The minimum canopy resistance for transpiration	82	s m^{-1}
ΔH	Latent heat of evaporation	2.45×10^6	J kg^{-1}
A_{roof}	The specific roof ventilation area	0.18	m^2 m^{-2}
A_{side}	The specific sidewall ventilation area	0.18	m^2 m^{-2}
$\Phi_{N,heat}$	Heat capacity of the direct air heater	100	W m^{-2}
$\Phi_{N,fog}$	Capacity of the fogging system	0.1	g $s^{-1}m^{-2}$
$\Phi_{N,CO2}$	Capacity of the external CO_2 source	6	mg s^{-1} m^{-2}
c_1	Coefficient of the stomatal resistance model to account for radiation effect	4.3	-

c_2	Coefficient of the stomatal resistance model to account for radiation effect	0.54	-
c_3	Coefficient of the stomatal resistance model to account CO2 effect	$6.1\times10^{-7}{}_{(day)}$,$1.1\times10^{-11}{}_{(night)}$	-
c_4	Coefficient of the stomatal resistance model to account for vapor pressure difference	4.85×10^{-6}	-
η_{mg_ppm}	CO_2 conversion factor from mg m^{-3} to ppm	0.544	mg $mg^{-1}.s^{-1}$
c_{leaf}	Leaf growth respiration coefficient	3.47×10^{-7}	mg $mg^{-1}.s^{-1}$
c_{stem}	Stem growth respiration coefficient	1.16×10^{-7}	mg $mg^{-1}.s^{-1}$
c_{fruit}	Leaf growth respiration coefficient	1.47×10^{-7}	m^2 mg^{-1}
SLA	Specific leaf area index	2.66×10^{-5}	mg $mg^{-1}.s^{-1}$
Q_{10}	coefficient of temperature effect on maintenance respiration	2	mg $mg^{-1}.s^{-1}$
α_{leaf_air}	Convective heat exchange coefficient from the canopy leaf to the greenhouse air	5	W $m^{-2}K^{-1}$
M_{H2O}	Molar mass of water	18	Kg $kmol^{-1}$
R	Molar gas constant	8314	J $kmol^{-1}K^{-1}$
γ	Psychrometric constant	65.8	Pa K^{-1}
τ_{scr}	The transmission coefficient of thermal screen	0.25	-
τ_{shade}	The transmission coefficient of shade net	0.5	-
$\rho_{m,flr}$	The density of floor	2300	kg m^{-3}
ρ_{cov}	The density of cover	2600	kg m^{-3}
Cap_{soil}	The heat capacity of soil	1.2×10^{4}	J kg^{-1} K^{-1}
$C_{p,cov}$	The specific heat capacity of cover	840	J kg^{-1} K^{-1}
Cap_{leaf}	The heat capacity of leaf	1200	J $K^{-1}m^{-3}$
h_{cov}	The thickness of cover	0.004	m

3. Plots of some simulation results

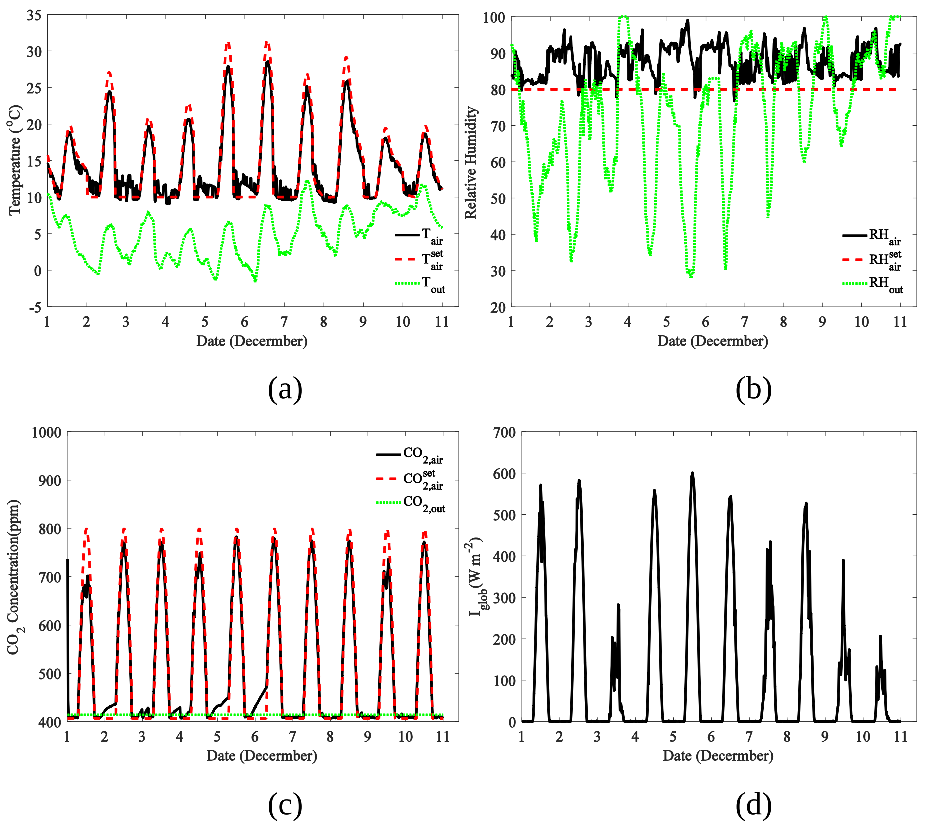

Fig.S4 Outside weather, greenhouse climate and its setpoint under the adaptive hybrid control situation during the period from Dec. 1, 2014 to Dec. 10, 2014. Superscript ‘set’ represents the setpoint of the greenhouse climate, and Subscript ‘air’ and ‘out’ represent the climate inside and outside of the greenhouse, respectively.

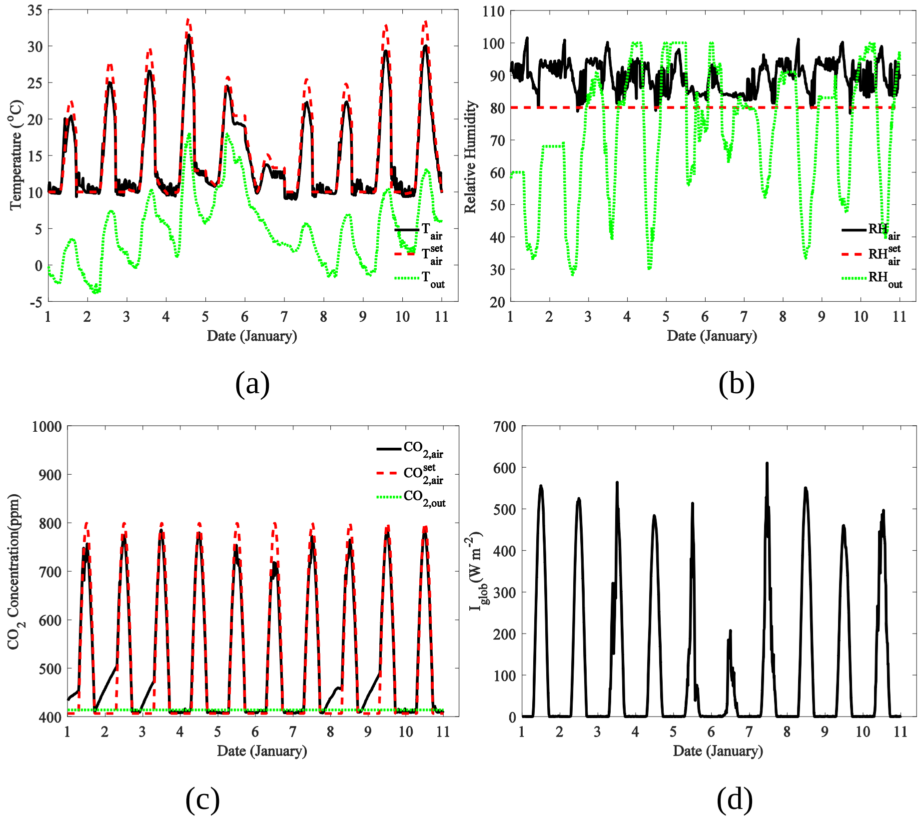

Fig.S5 Outside weather, greenhouse climate and its setpoint under the adaptive hybrid control situation during the period from Jan. 1, 2015 to Jan. 10, 2015. Superscript ‘set’ represents the setpoint of the greenhouse climate, and Subscript ‘air’ and ‘out’ represent the climate inside and outside of the greenhouse, respectively.

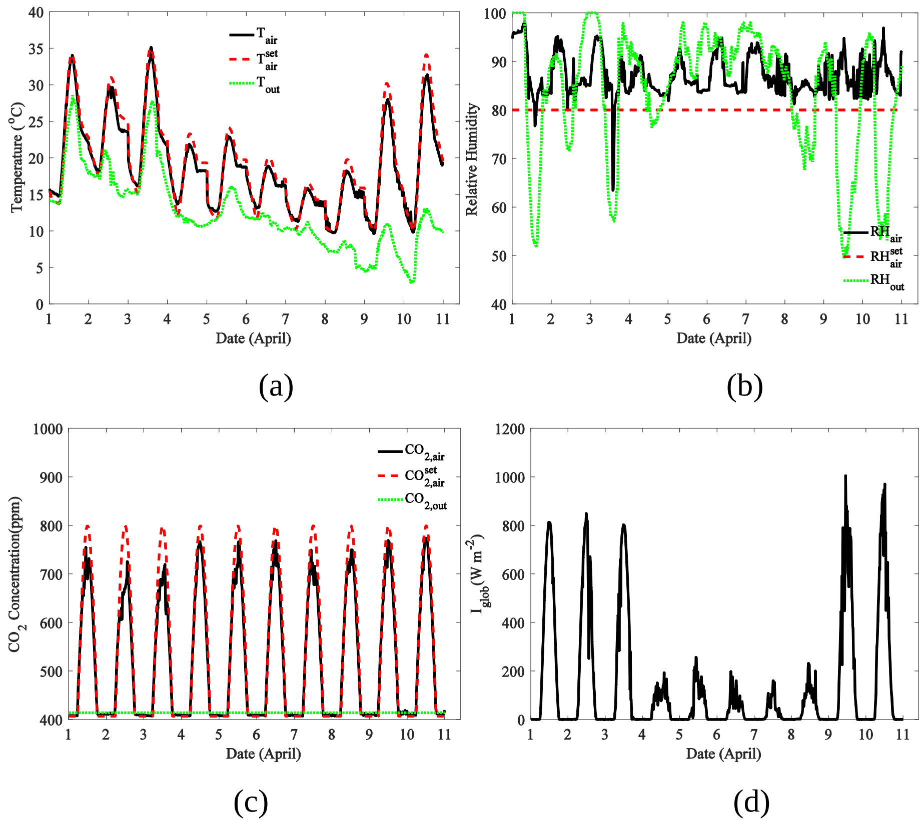

Fig.S6 Outside weather, greenhouse climate and its setpoint under the adaptive hybrid control situation during the period from April 1, 2015 to April 10, 2015. Superscript ‘set’ represents the setpoint of the greenhouse climate, and Subscript ‘air’ and ‘out’ represent the climate inside and outside of the greenhouse, respectively.

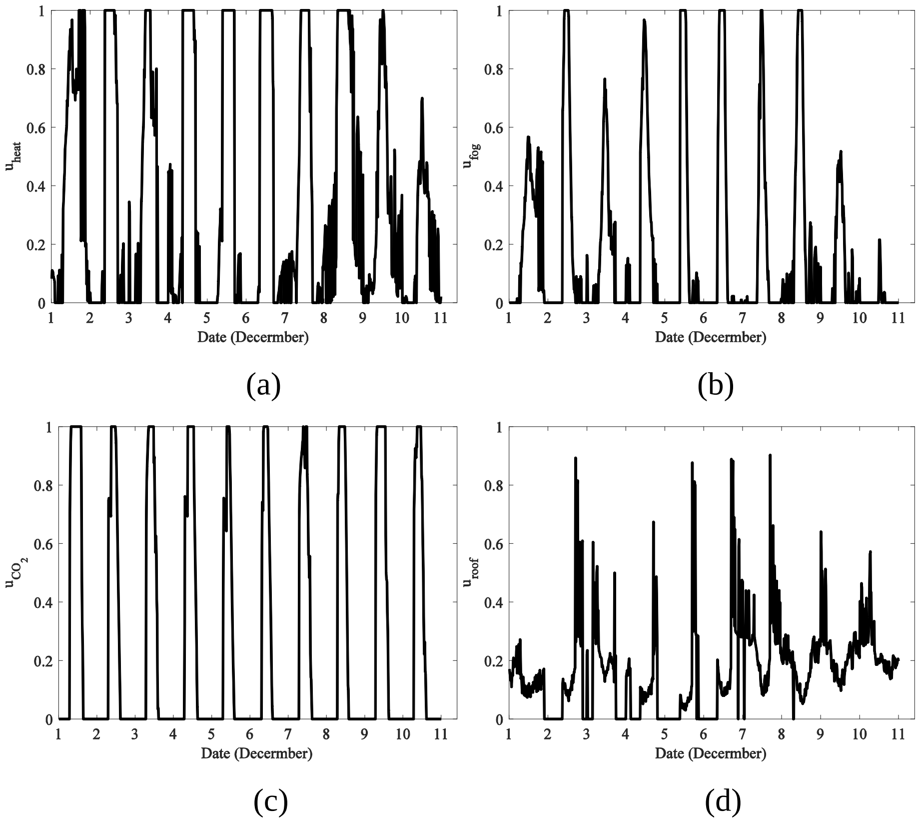

Fig.S7 The control signals of the heating, fogging, CO_2 injecting and ventilation during the period from Dec. 1, 2014 to Dec. 10, 2014.

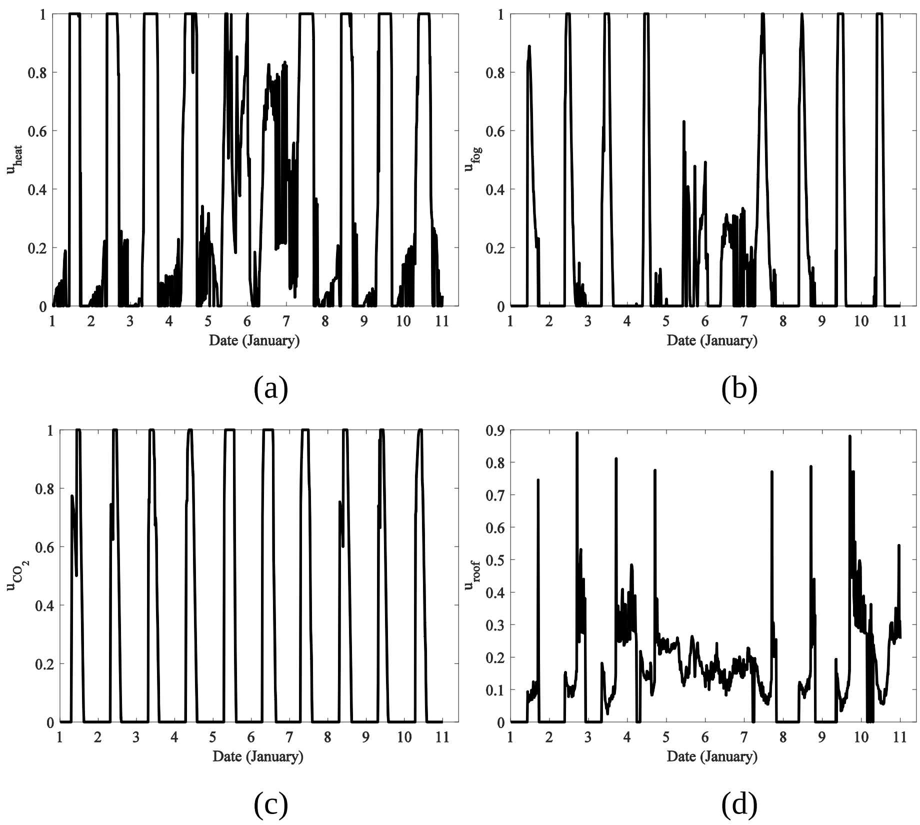

Fig.S8 The control signals of the heating, fogging, CO_2 injecting and ventilation during the period from Jan. 1, 2015 to Jan. 10, 2015.

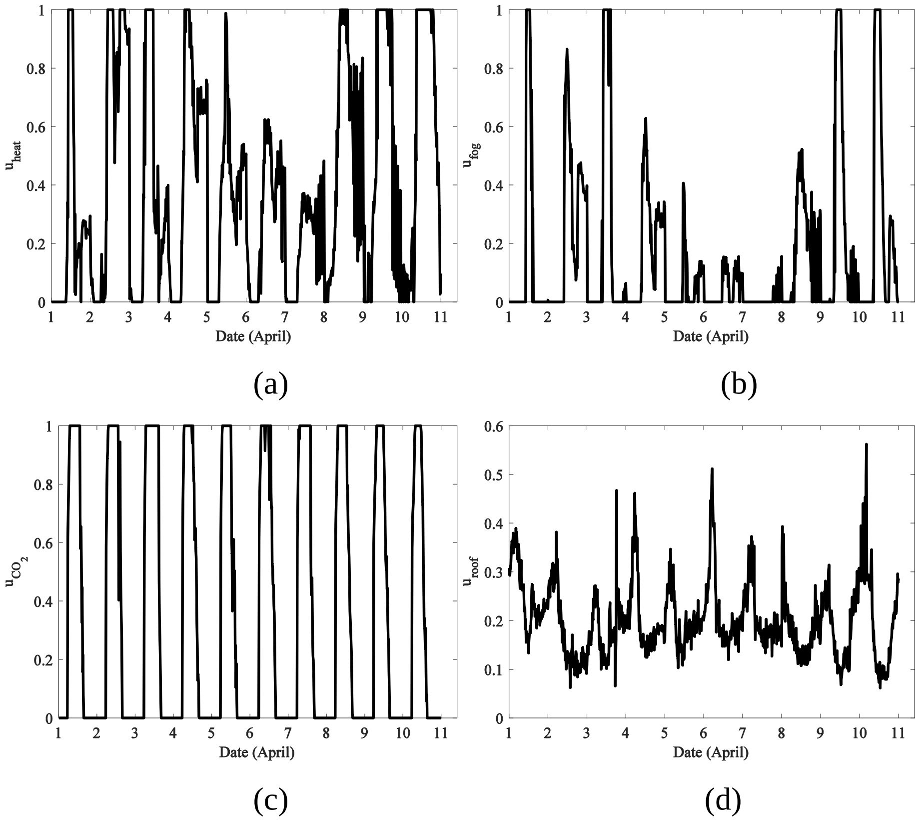

Fig.S9 The control signals of the heating, fogging, CO_2 injecting and ventilation during the period from April 1, 2015 to April 10, 2015.

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