Dynamic Mechanistic Modeling of Air Temperature and Humidity in the Greenhouses with On-Off Actuators

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Abstract
The mechanistic models of greenhouse microclimate can be used as the simulators for designing new control strategies. According to the on-off characteristics of the actuators in greenhouse in China, the operating state of a greenhouse was divided into several sub-states, and new mechanistic models of greenhouse air temperature and humidity were built. In order to validate the new models, the relevant environmental factors under three sub-states were measured in a glass greenhouse. The mean square error of greenhouse air temperature and relative humidity are 0.57°C and 2.8% respectively. These results indicate that the new models are suitable for the development of energy-saving control strategies of greenhouse microclimate in future.

Keywords: mechanistic model, air temperature, relative humidity, greenhouse, on-off actuators

1. Introduction
Many modern greenhouses have been imported in China as show-cases of modern agriculture from Western European countries in the past 30 years. However, few of such showcase greenhouses have been economically successful in China. These greenhouses consume too much energy. One major cause for the discrepancy in performance of these production systems in Europe and in China is the significant climatic differences between China (particularly in the subtropical regions) and the countries where the systems were developed [1]. Therefore, it’s necessary to develop suitable control strategies for the greenhouses in China. However, it’s inappropriate to test new control methods in an actual greenhouse directly, because it’s laborious and costly, and it even causes damage to the actuators and crops. It’s better to test new control methods in simulation at first, which is convenient and safe. The premise is that the mechanistic models of greenhouse microclimate must be built in advance. The purpose of this paper was to develop suitable mechanistic models of greenhouse air temperature and humidity, according to the characteristics of actuators in most greenhouses in China.

The mechanistic model of greenhouse microclimate is a group of dynamic energy and mass balance equations, the function of which is to simulate the dynamic behaviors of greenhouse microclimate. Many mechanistic models have been developed, such as GDGCM model [2, 3], KASPRO model [4, 5], MICGREEN model [6], SimGreC model [7], SIMICROC model [8], etc. Both GDGCM model and KASPRO model are developed according to the climatic conditions in Western European countries (Belgium and the Netherlands), where the air temperature is not too high in summer, and the natural ventilation and the shading are enough for cooling. So the ventilation is little described in the two models. MICGREEN model includes four energy-balance equations of cover, inside air, canopy surface and bare soil surface respectively of greenhouse in winter, but no actuators are considered in the model. Compared with MICGREEN model, both SimGreC model and SIMICROC model include a mass-balance equation of water vapor in greenhouse air additionally. Both window opening and heating are also considered in SimGreC model, while the side windows and overhead window are considered in SIMICROC model. However, in China, trapped by the construction cost and management level, many actuators use an on-off mechanism [9]. So the above models are not suitable to develop new control strategies for the greenhouses in China.

There are also some mechanistic models which just describe the dynamic behaviors of greenhouse microclimate under a particular operating state, for example, Teitel and Tann studied the transient response of the greenhouse air temperature and humidity under the...
natural ventilation state [10]; Willits built a mechanistic model under the mechanical ventilation state [11]; Ganguly and Ghosh presented a thermal model of a greenhouse under the fan-pad evaporative cooling state [12]; Du et al. developed a simulation model of greenhouse with a heat-pipe heating system [13]. However, we think that a perfect mechanistic model of inside air temperature and humidity should include all the common operating states of greenhouse. In this paper, according to the on-off characteristic of actuators, we built new mechanistic models of greenhouse air temperature and humidity, including the common operating states of a greenhouse.

2. Materials and Methods

The Venlo-type greenhouse is taken for example to illustrate the modeling process, because this type greenhouse is widely used in China. The structural representation of multi-span Venlo-type greenhouse is shown in Figure 1. The length, width and eaves height are marked as $L_g$, $W_g$ and $H_g$ respectively. The opening angle of each roof window is marked as $\alpha$. The main actuators installed in greenhouse are roof windows, fans, wet pads and shading screens. For some greenhouses, there are side windows, while there are no for others. It’s assumed that there are no side windows here.

In order to describe the air temperature and humidity in greenhouse accurately and meanwhile keep the modeling process not too complex, the following assumptions and simplifications are made: (1) the air temperature and humidity distribute homogeneously in the whole greenhouse; (2) the air density and specific heat capacity don’t change with temperature; (3) the losses of mass and energy caused by the gaps of greenhouse are neglected; (4) the exchanges of mass and energy between inside air and soil as well as that between inside air and crops are both neglected; (5) the long wave radiation is also neglected.

2.1. Modeling of Inside Air Humidity

Heating is not considered here, because it is seldom used in the greenhouses in Southern China area. The common on-off actuators are roof window, fans and wet pad. The three kinds of actuators make the greenhouse have three cooling methods, namely natural ventilation, mechanical ventilation and pad-fan cooling. The following model for describing the dynamic behaviors of water vapor density in greenhouse air is built:

$$
\begin{align*}
V_g \frac{d \rho_{\text{inv}}(t)}{dt} &= E_{\text{tran}}(t) - x_1 E_{\text{nv}}(t) - x_2 E_{\text{mv}}(t) - x_3 E_{\text{pf}}(t) - E_{\text{cond}}(t) \\
\text{s.t. } \sum x_j &\leq 1, \quad x_j = 0,1 \quad (j = 1, 2, 3)
\end{align*}
$$

where $V_g$ denotes the volume of greenhouse ($m^3$); $\rho_{\text{inv}}(t)$ the water vapor density in greenhouse ($g/m^3$); $t$ time (s); $E_{\text{tran}}(t)$ the change rate of inside water vapor density produced by crop transpiration ($g/s$); $E_{\text{nv}}(t)$ that caused by natural ventilation ($g/s$); $E_{\text{mv}}(t)$ that caused by mechanical ventilation ($g/s$); $E_{\text{pf}}(t)$ that caused by pad-fan cooling ($g/s$); $E_{\text{cond}}(t)$ that caused by water vapor condensation on the inner surface of cover layer ($g/s$); $x_j \ (j = 1, 2, 3)$ decision variables and have values of either 0 or 1 (0 denotes OFF and 1 ON). According to the actual
control process, it's known that there is at most one decision variable with the value 1 at any time. In order to make the equations not seem too complex, the time mark \( t \) is omitted in the following modeling process.

(1) Crop transpiration

The Penman-Monteith formula is the most common and reasonable model to calculate crop transpiration. In the case of neglecting the soil transpiration, the change rate of inside water vapor density produced by crop transpiration is described as follows [14, 15]:

\[
E_{\text{tran}} = A_f \frac{\Delta R'_{\text{in}} + 2 \rho_a C_v \text{LAI}(e'_{\text{in}} - e_{\text{a}})/r_{\text{s}}}{\lambda (\Delta + (1 + r_{\text{s}}/r_{\text{a}}) \gamma)}
\]

where \( A_f \) denotes the floor area of greenhouse (\( m^2 \)); \( \Delta \) the slope of the saturation vapor pressure - temperature curve (\( Pa/°C \)); \( R'_{\text{in}} \) the solar radiation obtained by the crop canopy inside (\( W/m^2 \)); \( \rho_a \) the air density(\( g/m^3 \)); \( C_v \) the air specific heat (\( J/(g°C) \)); \( \text{LAI} \) the leaf area index of crop (\( m^2 \) leaves/\( m^2 \) soil); \( e'_{\text{in}} \) and \( e_{\text{a}} \) the air saturated water vapor pressure and the actual vapor pressure in greenhouse respectively (\( Pa \)); \( \lambda \) the latent heat of water evaporation (\( J/g \)); \( r_{\text{s}} \) and \( r_{\text{a}} \) the stomatal resistance and the aerodynamic resistance of crop respectively (\( s/m \)); \( \gamma \) psychrometric constant (\( Pa/°C \)).

When the atmospheric pressure is not too high, the saturated water vapor pressure in greenhouse air is just related with air temperature. The saturated water vapor pressure in greenhouse air, the solar radiation obtained by the crop canopy inside and the slope of the saturation vapor pressure - temperature curve \( \Delta \) can be calculated as follows [16]:

\[
e'_{\text{in}} = e_{\text{zero}} \cdot \exp\left(17.4T_{\text{a}}/(239 + T_{\text{a}})\right)
\]

\[
R'_{\text{in}} = (1 - \exp(-k \cdot \text{LAI}))R_{\text{a}}
\]

\[
\Delta = 4158.6e'_{\text{in}}/(239 + T_{\text{a}})^2
\]

where \( e_{\text{zero}} \) denotes the saturated water vapor pressure at 0°C (\( Pa \)); \( T_{\text{a}} \) the inside air temperature (°C); \( k \) the extinction coefficient of crop canopy, dimensionless; \( R_{\text{a}} \) the solar radiation reached on the crop canopy inside (\( W/m^2 \)), which is the product of the solar radiation outside and the transmission coefficient of cover layer.

The computation expressions of the stomatal resistance and the aerodynamic resistance of crop are given as follows [17]:

\[
r_{\text{s}} = 200\left(1 + \exp\left(-0.05(R_{\text{a}} - 50)\right)\right)
\]

\[
r_{\text{a}} = 220d^{0.2}/v_{\text{in}}^{0.8}
\]

where \( d \) denotes the characteristic length of crop leaf (\( m \)); \( v_{\text{in}} \) the air velocity in greenhouse (\( m/s \)).

(2) Ventilation

Natural ventilation is the first choice for cooling in greenhouse because it consumes little energy. While when natural ventilation can’t meet requirements, mechanical ventilation is usually adopted for cooling. As the water vapor densities both inside and outside greenhouse are different, the inside water vapor density is changed when natural ventilation or mechanical ventilation start. The change rates of inside water vapor density caused by natural ventilation and mechanical ventilation can be calculated as follows:

\[
E_{\text{nv}} = \varphi_{\text{nv}} (\rho_{\text{in}} - \rho_{\text{av}})
\]

\[
E_{\text{mv}} = \varphi_{\text{mv}} (\rho_{\text{in}} - \rho_{\text{av}})
\]
where $\varphi_{nv}$ denotes the natural ventilation rate ($m^3/s$); $\rho_{ovw}$ the outside water vapor density ($g/m^3$); $\varphi_{mv}$ denotes the mechanical ventilation rate ($m^3/s$).

The mechanical ventilation rate is easy to calculate, which is determined by the ventilation rate of a single fan and the number of fans started. However, as the outside wind speed changes randomly, the natural ventilation rate is not easy to calculate. According to the related research results [18, 19], wind pressure is the main influence factor of natural ventilation rate, and hot pressure can be neglected in one of the three following conditions: (1) the outside wind speed exceeds 2 m/s; (2) the air temperature difference between inside and outside is very little; (3) the vertical dimension between the centre of air intake and that of air outlet is not long. The natural ventilation rate and the effective ventilation area can be calculated simply as follows:

$$\varphi_{nv} = (A_v/2) \chi \psi \alpha \sin(\alpha/2)$$

(10)

$$A_v = 2A_{out} \sin(\alpha/2)$$

(11)

where $A_{ev}$ denotes the effective ventilation area in greenhouse ($m^2$); $\chi$ the discharge coefficient, dimensionless; $\psi$ the integrated wind pressure coefficient, dimensionless; $v_{out}$ the average outside wind velocity ($m/s$); $A_{vent}$ the total area of ventilation windows ($m^2$).

(3) Pad-fan cooling

Pad-fan cooling is adopted in hot summer when neither natural ventilation nor mechanical ventilation meets cooling requirements. When pad-fan cooling starts, a lot of water mist is brought into the greenhouse air and the inside water vapor density changes obviously. The computational formula is similar to those of ventilation:

$$E_{pf} = \varphi_{pf} (\rho_{ovw} - \rho_{wet})$$

(12)

where $\varphi_{pf}$ denotes the ventilation rate of pad-fan cooling ($m^3/s$); $\rho_{wet}$ the water vapor density in the air which just passes through the wet pad ($g/m^3$), and it can be calculated as follows:

$$\rho_{wet} = \rho_{ovw} + \eta(\rho_{pad} - \rho_{ovw})$$

(13)

where $\eta$ denotes the evaporation efficiency of the wet pad, dimensionless; $\rho_{pad}$ the water vapor density on the wet pad surface ($m^3/s$). It’s assumed that the water vapor is saturated on the wet pad surface, and it can be calculated based on the state equation of ideal gas [20]:

$$\rho_{pad}^* = e_{pad}^* M / (R(T_{pad} + 273.15))$$

(14)

where $M$ denotes the molar mass of water (g/mol); $R$ the perfect gas constant (J/(mol°C)); $T_{pad}$ the surface temperature of the wet pad (°C); $e_{pad}$ the saturated water vapor pressure on the surface of the wet pad (Pa), which can be calculated by Eq.(3) with $T_{pad}$ instead of $T_{in}$.

(4) Water vapor condensation

When the inner surface temperature of cover layer is lower than the dew point temperature, condensation will occur on the inner surface of the cover materials. It occurs easily in winter. A simplified calculation formula of dew point temperature provided by Michell Instruments Ltd is adopted here. The uncertainty of dew point temperature is ±0.04 °C in the range of -45°C~+60°C.

$$T_d = \left[ 243.12 \ln \left( e_{in}^* / 611.12 \right) \right] / \left[ 17.62 - \ln \left( e_{in}^* / 611.12 \right) \right]$$

(15)
When the inner surface temperature of cover layer is lower than the dew point temperature, the loss of inside water vapor caused by condensation is calculated as follows [20]:

$$E_{\text{cond}} = 1.64 \times 10^{-3} A_s (T_{in} - T_{w})^{1/3} (\rho_{\text{sv}} - \rho_{\text{svw}})$$ (16)

where $A_s$ denotes the surface area of greenhouse ($m^2$); $T_{in}$ the inner surface temperature of cover layer (°C), and $T_{w} = \theta T_{in} + (1-\theta) T_{out}$, $\theta$ is a dimensionless weight; $\rho_{\text{svw}}$ the saturated water vapor density corresponding to the inner surface temperature of cover layer ($g/m^3$), the computational formula of which is similar to Eq.(14).

2.2. Modeling of Inside Air Temperature

Based on the above assumptions and the division of greenhouse operation state, a mechanistic model of greenhouse air temperature is built:

$$\rho_s V_g C_a \frac{dT}{dt} = Q_{\text{radin}}(t) - x_1 Q_{mv}(t) - x_2 Q_{pf}(t) - Q_{\text{exch}}(t) - Q_{\text{tran}}(t)$$ (17)

where $Q_{\text{radin}}(t)$ denotes the power change rate of solar radiation absorbed by greenhouse (W); $Q_{nv}(t)$ that caused by natural ventilation (W); $Q_{mv}(t)$ that caused by mechanical ventilation (W); $Q_{pf}(t)$ that caused by pad-fan cooling (W); $Q_{\text{exch}}(t)$ that caused by energy exchange between inside and outside air through cover layer (W); $Q_{\text{tran}}(t)$ that caused by crop transpiration (W). The time mark $t$ is also omitted in the following, just like that in the modeling process of water vapor density. All the items in the right side of Eq.(17) can be expressed as follows successively [6, 21]:

$$Q_{\text{radin}} = A_{\text{tau}} R_{\text{out}}$$ (18)

$$Q_{nv} = \rho_s C_a \varphi_{nv} (T_{in} - T_{out})$$ (19)

$$Q_{mv} = \rho_s C_a \varphi_{mv} (T_{in} - T_{out})$$ (20)

$$Q_{pf} = \rho_s C_a \varphi_{pf} (T_{in} - T_{wet})$$ (21)

$$Q_{\text{exch}} = A_{\text{tau}} \omega (T_{in} - T_{out})$$ (22)

$$Q_{\text{tran}} = \lambda E_{\text{tran}}$$ (23)

where $\tau$ denotes the transmission coefficient of cover layer, dimensionless; $R_{\text{out}}$ solar radiation power outside greenhouse ($W/m^2$); $T_{wet}$ the temperature of wet air that just passes through the wet pad (°C), and it can be calculated as follows [20]:

$$T_{wet} = T_{out} + \eta (T_{\text{pad}} - T_{out})$$ (24)

2.3. Environmental Data Acquisition of Greenhouse

In order to verify the new models, the relevant environmental factors of a Venlo-type glass greenhouse were measured. The greenhouse is 60 meters long and 30 meters wide. Four ventilation fans are installed on one side wall and a wet pad is installed on the opposite. The ventilation rate of each fan is 36000 $m^3/h$. An ornamental butterfly orchid plant was planted inside, about 1/5 of the greenhouse area. A plastic thermal screen was installed in the greenhouse with about three meters high, so the roof windows can be opened. The relevant environmental factors can be measured under the three sub-states: passive state, mechanical ventilation and pad-fan cooling. In the passive state, all the actuators are not working.
Two temperature-humidity recorders (RC-4HA type) were adopted to measure the air temperature and relative humidity both inside and outside the greenhouse. The measurement accuracy for temperature is ±0.4°C, and that of relative humidity is ±3%. A luxometer (HS1010A type) was adopted to measure the external solar illuminance, which had a measurement range of 0~200 kLux, and a measurement accuracy of ±4% (<10 kLux) and ±5% (>10 kLux). However, the unit of solar radiation is $W/m^2$ in the above expressions. It is necessary to achieve the conversion of the two different units. The conversion coefficient varies with the light wavelength. A conversion coefficient of 555nm light is adopted for yellow-green light, which is the most sensitive to the human eye. Eq.(2) can be rewritten as follows:

$$ R_{\text{out}} = \mu I_{\text{out}} $$

where $\mu$ is the conversion coefficient from solar illuminance to radiation power ($W/(m^2Lux)$); $I_{\text{out}}$ the external illuminance ($Lux$).

The measurement experiment was done on the morning of April 15 2014. The temperature upper limit was set to 34°C. The measurement period was set to 1 minute. The inside air temperature and relative humidity were 23.2°C and 71.6% respectively at 8:00 am. All the actuators were off. The inside air temperature rose and the relative humidity fell gradually with time. At 10:15 am the inside air temperature reached up to 34.1°C, and then the three fans were turned on for mechanical ventilation. The inside air temperature fell rapidly, while the relative humidity also fell because the outside relative humidity was lower. The mechanical ventilation lasted 15 minutes. The air temperature and relative humidity fell to 25.6°C and 45.1% respectively at 10:30 am. Then the fans were turned off. The greenhouse returned to the passive sub-state. The inside air temperature began to rise again. At 11:06 am the inside air temperature reached up to 34.2°C. Then the three exhaust fans and the wet pad were turned on for cooling. The inside air temperature fell rapidly, while the relative humidity rose, because large amount of water mist was brought into the greenhouse air. After 15 minutes, the fans and the wet pad were both turned off. The inside air temperature fell to 21.7°C and the relative humidity rose to 94.4%. During the pad-fan cooling process, the temperature of water poured on the pad was about 14.5°C without obvious fluctuation. The measurement experiment was stopped at 12:00 am. The relevant environmental factors measured both inside and outside greenhouse from 8:00 am to 12:00 am were plotted in Figure 2.

![Figure 2. Relevant environmental factors measured from 8:00 am to 12:00 am](image-url)
2.4. Simulation

The data of greenhouse air temperature and relative humidity at 8:00 am is taken as the initial value of the mechanistic models. The data of outside environmental factors are used as the inputs of the models to simulate the dynamic characteristics of greenhouse air temperature and relative humidity. The mechanistic models can be verified by the comparison of the simulation results and the measurement. Some relevant explanations are as follows. The dependent variable in the mechanistic model of humidity is the water vapor density, while what can be directly measured is the relative humidity. So the water vapor density should be transformed into the relative humidity. The relative humidity is the quotient of the water vapor density divided by the saturated water vapor density. In addition, the inertia of fans was simply considered in the simulation. The function of fans and wet pad at the next time instant after starting was set to half of that when they reached full-speed operation.

The models were programmed in Matlab software. The relevant parameter settings in simulation were listed in Table 1. The parameters of greenhouse were set according to the experimental greenhouse. We measured the width of 20 leaves of the butterfly orchid plant stochastically, and took their average as the characteristic length of leaf. The extinction coefficient of butterfly orchid canopy was in the range of 0.21~0.29 [22, 23], and was set to 0.25 by try and error method.

Table 1 The relevant parameter settings in simulation

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_g$</td>
<td>Length of greenhouse</td>
<td>60 m</td>
<td>measured</td>
</tr>
<tr>
<td>$W_g$</td>
<td>Width of greenhouse</td>
<td>30 m</td>
<td>measured</td>
</tr>
<tr>
<td>$H_g$</td>
<td>Eaves height of greenhouse</td>
<td>5 m</td>
<td>measured</td>
</tr>
<tr>
<td>$l_e$</td>
<td>Length of each span</td>
<td>6 m</td>
<td>measured</td>
</tr>
<tr>
<td>$h_e$</td>
<td>Height of each span</td>
<td>1 m</td>
<td>measured</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Maximal angle of roof window</td>
<td>$\pi$/4</td>
<td>assumed</td>
</tr>
<tr>
<td>$\rho_a$</td>
<td>Air density</td>
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</tr>
<tr>
<td>$C_s$</td>
<td>Air specific heat</td>
<td>1.012 J/(g°C)</td>
<td>constant</td>
</tr>
<tr>
<td>$\omega_g$</td>
<td>Heat transfer coefficient of glass</td>
<td>6.4 W/m²°C</td>
<td>[25]</td>
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<tr>
<td>$\omega_g$</td>
<td>Heat transfer coefficient of glass and plastic</td>
<td>4.8 W/m²°C</td>
<td>[25]</td>
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<td>$r_g$</td>
<td>Transmission coefficient of glass</td>
<td>0.89</td>
<td>measured</td>
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<td>$r_p$</td>
<td>Transmission coefficient of plastic</td>
<td>0.8</td>
<td>measured</td>
</tr>
<tr>
<td>$\theta_{s,a}$</td>
<td>Saturation vapor pressure at 0°C</td>
<td>610.78 Pa</td>
<td>constant</td>
</tr>
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<td>Leaf area index of crop canopy</td>
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<tr>
<td>$\lambda$</td>
<td>Latent heat of evaporation of water</td>
<td>2450 J/g</td>
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<td>$\gamma$</td>
<td>Psychrometric constant</td>
<td>66 Pa/°C</td>
<td>constant</td>
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<tr>
<td>$k$</td>
<td>Extinction coefficient of canopy</td>
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<td>[24]</td>
</tr>
<tr>
<td>$d$</td>
<td>Characteristic length</td>
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<td>measured</td>
</tr>
<tr>
<td>$\chi$</td>
<td>Discharge coefficient</td>
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<td>[18]</td>
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<td>Integrated wind pressure coefficient</td>
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<td>[18]</td>
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<td>Perfect gas constant</td>
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<td>Evaporation efficiency of wet pad</td>
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<td>Surface temperature of the wet pad</td>
<td>14.5 °C</td>
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<tr>
<td>$\mu$</td>
<td>Conversion coefficient from illuminance to power</td>
<td>$1.46\times10^{-3}$ W/(m²Lux)</td>
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<td>$\theta$</td>
<td>The dimensionless weight for the calculation of inner surface temperature of cover layer</td>
<td>0.7</td>
<td>estimated</td>
</tr>
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</table>

3. Results and Discussion

The dynamic simulation and the measurement results of the greenhouse air temperature are plotted in Figure 3; while those of relative humidity are plotted in Figure 4. It can be seen that the new models can simulate the dynamic behaviors of the greenhouse air temperature and relative humidity accurately. The mean square error of greenhouse air temperature and relative humidity are 0.57 °C and 2.8% respectively [24, 25].

In the beginning, the greenhouse is in the passive sub-state. The simulation results of greenhouse air temperature and relative humidity are both in good agreement with the measurement. After the start of mechanical ventilation, some deviations occur. The simulation of temperature is lower than the measurement, while the simulation of relative humidity is higher. The main reason is that there is a plastic screen fixed at the top of the greenhouse. The space between the plastic screen and the greenhouse roof is large. When mechanical
ventilation is started, the greenhouse air temperature falls quickly, while the air temperature in the specific space is still higher. So the above energy begins to transfer into the greenhouse air through the plastic screen. The screen is not considered in the simulation, so the simulation of temperature is lower than the measurement and the simulation of relative humidity is higher. Just because of the plastic screen, the dynamic characteristics of greenhouse air temperature and relative humidity under the natural ventilation state is not verified.

The simulation results are acceptable, so the new models are helpful for us to develop the control strategies of greenhouse microclimate for saving energy in future. In South China, in spring and autumn, cooling is usually needed for greenhouse in sunny day. Natural ventilation, mechanical ventilation and pad-fan cooling can all meet the cooling requirements well. The energy consumption of greenhouse cooling is expected to be minimized on the premise of meeting the control requirements. However, the problem is that it is not easy for growers to choose what kind of cooling mode to use and when to choose. On the basis on the mechanistic models, we can research the energy-saving control strategies of greenhouse microclimate. The models are just suitable for the simulation of greenhouse microclimate in spring and autumn, as they are only verified in mid April (spring). If there is more than one cooling modes that can meet the control requirements, the mechanistic models must be modified and re-verified.

4. Conclusions
The on-off characteristics of actuators make the greenhouses own many different operating sub-states. The new mechanistic models of greenhouse air temperature and humidity were built. Compared with traditional mechanistic models, the new models are simple and easy to realize, and can be used as a simulator for our future research work.

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