A SWITCHING CONTROL STRATEGY OF GREENHOUSE COOLING SYSTEM BASED ON TEMPERATURE PREDICTION MODEL FOR ENERGY SAVING
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基于温度预测模型的温室降温系统的节能切换控制

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ABSTRACT
In order to reduce the energy consumption of greenhouse cooling in subtropical and tropical regions, we proposed a switching control strategy based on temperature prediction model. Due to the facilities driven by the on-off actuators in many greenhouses, the cooling system was treated as a hybrid system with discrete operating modes. When the indoor air temperature reaches the upper limit set by growers, the IARX model in each mode is used to predict the indoor air temperature over a specified horizon respectively. Then the energy consumption of each mode is pre-estimated and the mode with minimum estimation is selected. The control strategy was simulated. The energy saving potential of the proposed control strategy is related to a variety of factors. In this simulation, the results indicate that the control strategy saves 15.4% energy within the temperature range (20°C, 30°C); while it saves 24.6% energy within the temperature range (24°C, 30°C), compared with a reference with fixed switching rules. Finally, the main influencing factors of energy consumption were discussed. The conclusions are instructive for the future application of the control strategy.

摘要
为减少热带和亚热带地区温室降温能耗，提出了一种基于温度预测模型的切换控制策略。由于许多温室内的设备采用开关控制，因此把降温系统看作为带有离散运行模式的混杂系统。当温室内空气温度超过设定上限时，分别使用每种模式下的 IARX 温度预测模型预测未来有限时域内温度的变化。然后评估每种模型的能耗，并选择出能耗最小的那种运行模式。对该控制策略进行了仿真。其节能潜能与多种因素有关。在该仿真中，与一个使用固定切换规则的参考控制方法相比，当温度范围为时(20°C, 30°C)，该控制策略可以节能 15.4%；而当温度范围为(24°C, 30°C)，该控制策略可以节能 24.6%。最后讨论了影响能耗的最要因素。相关结论对于该控制策略的今后使用具有指导意义。

INTRODUCTION
A greenhouse is a plastic or glass building that can provide a suitable microclimate for plants, protecting them from severe and variable outdoor weather conditions. As a result, many greenhouses can operate all year round and produce much higher yields than the open land cultivation. However, the greenhouse production system consumes much more energy. The energy is consumed mainly for heating in cold regions (*Sethi et al., 2008; Vadiee et al., 2014*), and for cooling in subtropical and tropical regions (*Kumar et al., 2009; Sethi et al., 2007*). South China is located in the subtropical region, so the greenhouses in this area usually need cooling in most time of a year. In order to reduce the consumption of electric energy and fossil fuels for greenhouse cooling, some researchers tried to use renewable energy, such as solar energy (*Chungloo et al., 2007; Cuce et al., 2016;*), geothermal energy (*Ozgener et al., 2010; Sethi et al., 2007*), etc. The use of renewable energy has a significant potential to reduce the consumption of conventional energy, but their systems are very complicated and the initial construction costs are very high, so that it is difficult to popularize these alternative methods. Another way to reduce the consumption of conventional energy is to design new control methods. Because the facilities in many greenhouses are driven by the on-off actuators (*Teitel et al., 2004*), it's difficult to use the conventional control methods, such as PID control (*Hu et al., 2010*), model predictive control (*Blasco et al., 2007*), fuzzy control (*Nachidi et al., 2010*), etc., and the operating mode of greenhouse cooling system can be divided into different sub-modes.

The greenhouse control system is treated as a hybrid system in this paper, due to the interaction between discrete on-off control signals and continuous environmental factors (*Lin et al., 2014*).

At present, hybrid systems have been widely applied in many fields (*Balluchi et al., 2013; Febbraro et al., 2016*), but rarely used in the greenhouse control system. Yang et al. adopted hybrid automata and studied the modeling and control of the temperature system in a greenhouse with only one on-off ventilation window (*Yang et al., 2011*). Chu et al. also studied the temperature control system based on hybrid automata in a greenhouse with three facilities, i.e., a roof window, a fan and a wet pad (*Chu et al., 2015*). However, the energy-saving issue was not considered in their studies. Another problem is that the design of switching rules is very complicated when there are multiple facilities, because several environmental factors have to be taken into account, such as indoor and outdoor air temperature, solar radiation, etc.

We proposed a switching control strategy of different cooling modes based on temperature prediction model for energy saving, because some simple temperature prediction models have been developed for control purposes (Frausto et al., 2003; Xu et al., 2016). The rest of the article is organized as follows. In Material and Method section, the proposed switching control strategy for energy saving is described at first. Then the simulation experiments are designed and a mechanistic model is used to test the energy-saving effect of the proposed control strategy. In Results section, the simulation results are introduced at first. Then, the energy-saving potential of the proposed control strategy is analysed by comparison with a reference one with fixed switching rules. At last, the main influencing factors of energy consumption are also discussed. The paper is concluded at last.

MATERIAL AND METHODS

Switching control strategy for energy saving

In subtropical and tropical regions, there are usually multiple cooling facilities installed in a greenhouse. Four common kinds of facilities are considered in this research, i.e., roof windows, fans, a wet pad and external shading net. Assume that they are all driven by the on-off actuators, which is in accordance with the actual situation of many greenhouses. According to the first three kinds of facilities, the greenhouse operation is divided into three modes, i.e., natural ventilation mode, mechanical ventilation mode and pad-fan cooling mode. When all the facilities don't work, the operating mode is called passive mode in this paper. The operation process can be regarded as a switching one among the four modes, and the greenhouse is in only one of the four modes at any time. The shading net also affects the indoor air temperature, but it is not used to divide the operating modes, because it is folded or unfolded, mainly depends on the solar radiation intensity, having little containment relationship with the above four operating modes. Therefore, the shading net can be folded or unfolded, no matter that the greenhouse is in any of the operating modes. The switching control system of the greenhouse is shown in Fig.1. The outdoor environmental factors are used as input to the controller to facilitate the construction of indoor air temperature prediction model.

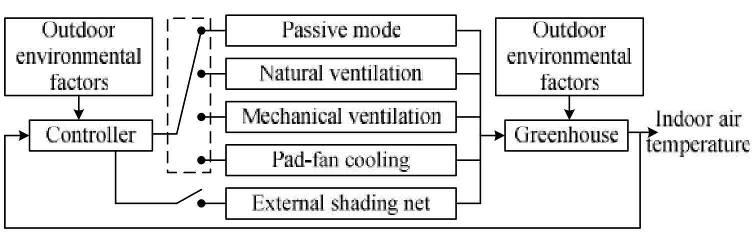

Fig.1 - The greenhouse cooling system

We proposed a new switching control strategy based on temperature prediction model to reduce the energy consumed for greenhouse cooling. At first, it's necessary to construct the prediction model of indoor air temperature in each cooling mode. At present, there are three kinds of prediction models, i.e., mechanistic model (*Singh et al., 2006*), ARX model (auto regressive prediction model with external variables) (*Frausto et al., 2003*) and neural network model (*Frausto et al., 2004*). The ARX model is simpler and has smaller computational burden than the other two kinds, so it is often used for control purposes. We have constructed the temperature prediction models in different operating modes based on the analysis of mechanistic models, called IARX (incremental ARX) model (*Xu et al., 2016*). The IARX models have fewer coefficients than typical ARX models, so they are more suitable for online identification in real-time control. The IARX prediction models of indoor air temperature in the natural ventilation mode and mechanical ventilation mode have the same form, shown as Eq.(1); while the prediction model in the pad-fan cooling mode is shown as Eq.(2).

$$\Delta T_i(k+1) = \sim_1 \Delta T_{oi}(k) + \quad_1 R_{out}(k) + \text{£} \tag{1}$$

$$\Delta T_i(k+1) = \sim_1 \Delta T_{oi}(k) + \quad_1 R_{out}(k) + \text{¥}_1 \Delta T_{pi}(k) + \text{£} \tag{2}$$

where $\Delta T_i(k+1)$ denotes the difference of indoor air temperature at the time instants $k+1$ and k (°C); $\Delta T_{oi}(k)$ the difference of outdoor and indoor air temperature at the time instant k (°C); $\Delta T_{pi}(k)$ the difference of indoor air temperature and that of the wet air that just passes through the pad at the time instant k (°C); $R_{out}(k)$ the solar radiation intensity at the time instant k (W/m^2); α_1, β_1, γ_1 and ε are all coefficients.

When the models are used to predict temperature at the time instant $k+i$ (i>1), it is necessary to provide the data of relevant environment factors at time $k+i$-1. However, the environmental data at future time instants are unknown in the actual control process. We will adopt the lazy man weather prediction method (*Tap et al., 1996*), in which the environmental factors remain unchanged over a specified horizon. The prediction method is effective when the horizon is not too long.

Assume the greenhouse is in the passive mode and the shading net is folded at the beginning. When the indoor air temperature reaches the upper limit, the model in each cooling mode is used to predict the indoor air temperature over a specified horizon respectively. Natural ventilation is the first choice because it consumes very little energy. As long as the predicted temperature in the natural ventilation mode is within the set range, this mode is selected directly and it is not necessary to consider the other two cooling modes. If the natural ventilation mode cannot reduce the indoor air temperature below the upper limit, the other two cooling modes will be adopted. Different from the natural ventilation mode, the mechanical ventilation mode and pad-fan cooling mode both consume much more energy. Of course, their capacities for cooling are significantly enhanced. In particular, the pad-fan cooling mode can reduce the indoor air temperature lower than that outside. In order to forbid the two cooling modes to run for too long time, we set the selection and stopping criteria for the two modes. The mechanical ventilation mode is taken for example. When the indoor air temperature reaches the upper limit and the predicted temperature over a specified horizon in the natural ventilation mode is also higher than the upper limit, the temperature model in the mechanical ventilation mode is used to predict over a specified horizon. If the predicted temperature can reach the lower limit, the cooling mode may be selected. The cooling mode is stopped when the indoor air temperature reduces to the average of the upper and lower limits. The selection and stopping criteria can ensure that the running time of mechanical ventilation is not more than the prediction horizon. The selection of pad-fan cooling mode is the same. If only one of the two cooling modes meets the selection criterion, it will be selected. If both modes meet it, it's required to make further judgments between them. We pre-estimate the energy consumption of the two cooling modes based on the prediction results over a specified horizon respectively. The algorithm is shown in Eq.(3), and the cooling mode with the smaller estimation will be selected.

$$\begin{aligned} & J = P \cdot n \cdot \Delta t \\ & s.t.\ T_{pred}\left(k+n \mid k\right) >= T_a \\ & \quad T_{pred}\left(k+n+1 \mid k\right) < T_a \\ & \quad 1 < n < N \end{aligned} \tag{3}$$

where the letter J denotes the energy consumption (J); P denotes the operating power of cooling mode (W); Δt the sampling period (s); N the length of prediction horizon (measured by the number of sampling periods); n the length of the continuous operation of cooling mode; $T_{pred}(k+j|k)$ the prediction value of indoor air temperature at the time instant $k+j$ (°C); T_L the lower limit (°C); T_a the average of the upper and lower limits (°C).

The selection process of cooling modes will be repeated every time when the indoor air temperature reaches the upper limit. Assume that the pad-fan cooling mode can meet the cooling requirements in any case, which is consistent with the real situations of many greenhouses. In the above control process, two thresholds are set for the shading net. When the solar radiation intensity exceeds the high threshold, the shading net is unfolded; while when the solar radiation intensity reduces to the low threshold, the shading net is folded. The difference between the two thresholds is helpful to avoid frequent switching of the shade net. The accuracy of temperature prediction models is very important to the switching control strategy. In order to obtain good accuracy, the receding horizon method is adopted to update the model coefficients in time (*Tap et al., 1996*). Therefore, the switching control of cooling modes can be implemented for energy saving.

Simulation experiments

We have constructed a mechanistic model of Venlo-type glass greenhouse microclimate to develop new control strategies and the discrete on-off control characteristics are fully considered (*Xu et al., 2016*). The mechanistic model of greenhouse temperature system is shown as Eq.(4), and we will use it to simulate the proposed switching control strategy.

$$\begin{cases} {}^{\circ}{}_a V_g C_a \dfrac{dT_{in}(t)}{dt} = Q_{radin}(t) - x_1 Q_{nv}(t) - x_2 Q_{mv}(t) - x_3 Q_{pf}(t) - Q_{exch}(t) - Q_{tran}(t) \\ s.t.\ \sum x_j \le 1,\ \ x_j = 0,1\left(j = 1,2,3\right) \end{cases} \tag{4}$$

where ρ_a denotes the air density(g/m^3); V_g the greenhouse volume (m^3); C_a the air specific heat (J/(g°C)); $T_{in}(t)$ the indoor air temperature (°C); t time (*s*); $Q_{radin}(t)$ the solar radiation power received in the greenhouse (W); $Q_{nv}(t)$ the power loss caused by natural ventilation (W); $Q_{mv}(t)$ the power loss caused by mechanical ventilation (W); $Q_{pf}(t)$ the power loss caused by pad-fan cooling (W); $Q_{exch}(t)$ the power loss caused by the energy exchange through cover layer (W); $Q_{tran}(t)$ the power loss of crop transpiration (W); x_j (j=1, 2, 3) decision variables and have values of either 0 or 1 (0 denotes OFF and 1 ON). There is at most one decision variable with the value 1 at any time, according to the operating process of greenhouse described in above switching control strategy section.

Before simulation, the data of four outdoor environmental factors should be provided, i.e., outdoor air temperature, relative humidity, solar radiation intensity and wind speed. A sunny day, Apr. 22, 2014 in Nanjing area is selected. Because cooling is not necessary at night, the control experiments are only simulated in day time and the simulation period is set to 7:30-16:30. The four outdoor environmental factors during this period are shown in Fig. 2.

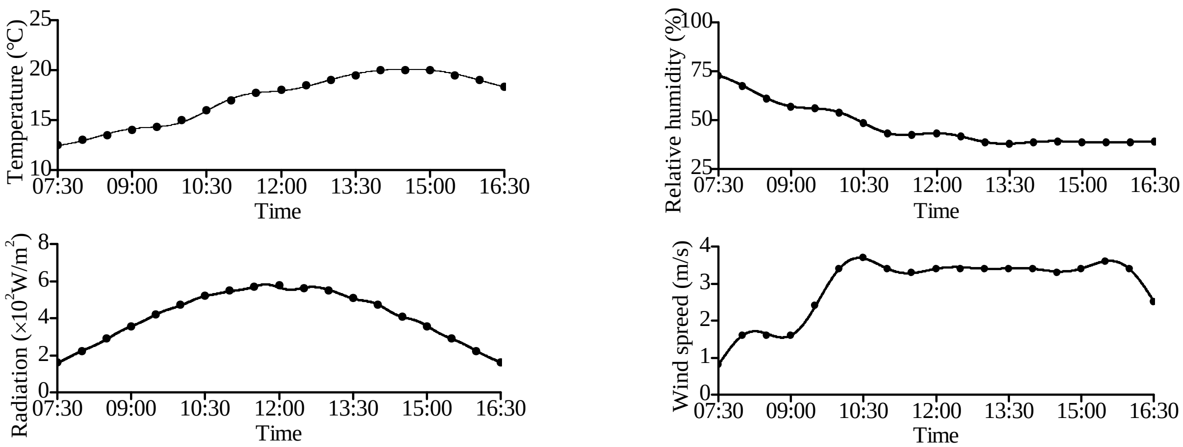

Fig. 2 - Four outdoor environmental factors

The facilities in simulation are consistent with that in the greenhouse which is used to verify the above mechanistic model. There are four ventilation fans, which are controlled by the same on-off drive signal. The greenhouse operates in mechanical ventilation mode when only the fans are switched on. The total area of roof windows is about tenth of the greenhouse area, with the maximal opening angle 30°. The greenhouse operates in mechanical ventilation mode when only the roof windows are switched on. There is a shade net above the greenhouse, the light transmission of which is about 50%. The thresholds for the shading net are set to 420 W/m^2 and 400 W/m^2. The IARX model includes solar radiation intensity, so the working state of shading net will affect the prediction results. The IARX models expressed in Eq.(1) and Eq.(2) are revised based on the on-off characteristic of shading net, and the revised IARX models are as follows respectively.

$$\Delta T_i(k+1) = \sim\Delta T_{oi}(k) + \quad (1 - x_4 ¦)R_{out}(k) + £ \tag{5}$$

$$\Delta T_i(k+1) = \sim\Delta T_{oi}(k) + \quad (1 - x_4 ¦)R_{out}(k) + ¥\Delta T_{pi}(k) + £ \tag{6}$$

where x_4 is the control signal of shading net (0 denotes OFF and 1 ON); η the light transmission (50%).

The operation powers of all facilities are required to calculate the energy consumption of greenhouse operation. The rated power of each fan is 1KW, and that of wet pad is 2KW. While compared with fans and wet pad, the energy consumption of roof windows and the shading net is very little, so they are neglected. It has been found that the indoor air temperature can reach a steady state within 10 minutes after the greenhouse entered into a new operating mode in actual tests (*Xu et al., 2016*), so the prediction horizon is set to 10 minutes. In order to study the influence of the upper and lower limits and the set range of temperature on the energy consumption, we set three temperature ranges. The butterfly orchid plant were potted in greenhouse when the mechanistic model was verified (*Xu et al., 2016*), so the temperature ranges are set as (20°C, 30°C), (24°C, 30°C) and (22°C,32°C), and they are numbered as case 1, 2 and 3, for easy identification. The above simulation experiments will be done in the three cases.

The IARX prediction models should be identified at first before use. For convenience, for the first three cooling requirements, the greenhouse is forced to enter into the three cooling modes successively. In order to obtain enough environmental data for model identification, the sampling period is set to 30s. After the first three cooling actions, the proposed control strategy is adopted for the greenhouse cooling system. As previously mentioned, the receding horizon method is adopted to update the model coefficients.

In order to explore the energy saving potential of the proposed control strategy, we designed a reference one without any temperature prediction model. The reference control strategy operates with fixed switching rules, which is described as follows. At the beginning, assume the greenhouse is in the passive mode and the shading net is folded. When the indoor air temperature reaches the upper limit, the natural ventilation mode is adopted at first. If the natural ventilation mode cannot meet the cooling requirement, the mechanical ventilation mode will be adopted. In order to prevent the fans from running for too long time, if the indoor air temperature cannot be reduced to the average of the upper and lower limits within five minutes, the greenhouse will be forced to transfer into the pad-fan cooling mode. When the indoor air temperature reaches the upper limit every time, the cooling mode adopted last time will be adopted at first. After unfolding the shading net, the switching process will repeat the above switching rules, and the natural ventilation mode is the first choice for cooling. Except for the switching rules, the other settings are the same as that in the proposed control strategy. The control strategies are programmed and simulated in MATLAB software.

RESULTS

The dynamic behaviours of indoor air temperature in the three cases are shown in Fig. 3 to Fig. 8. The simulation results indicate that the two switching control strategies can meet the cooling requirement. The operating times of three cooling modes are counted in the three cases for the two control strategies, and listed in Table 1. The energy consumption of the two control strategies is calculated and shown in Table 2. The results in case 1 and case 2 indicate that the proposed control strategy has a good potential for energy saving. The results in case 3 will be analysed specially below.

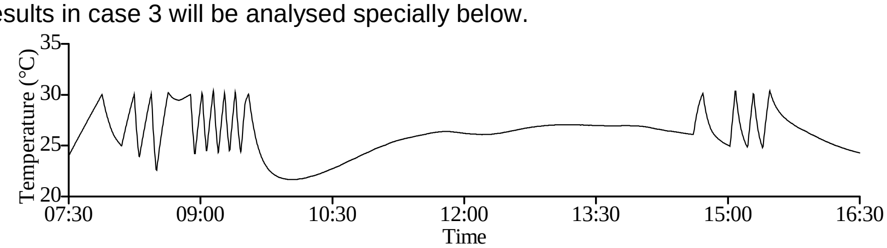

Fig.3 - The indoor air temperature of the proposed control strategy in case 1

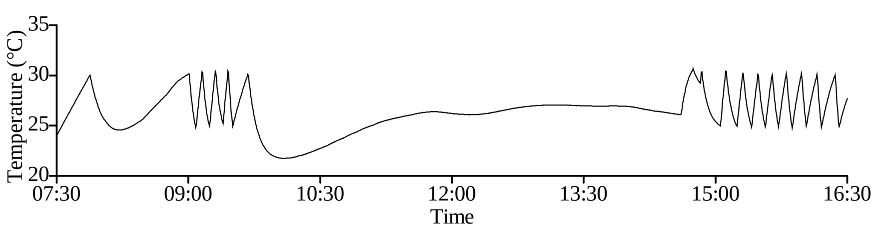

Fig.4 - The indoor air temperature of the reference control strategy in case 1

In case 1 and case 2, the dynamic behaviours of indoor air temperature simulated by the two control strategies are different, and the main difference appears in the later stage of the simulation process. The reason is as follows. For the proposed control strategy, the mode switch is based on the real-time prediction results. The prediction results of temperature models change with the outdoor environmental factors, so the proposed control strategy can choose the natural ventilation mode in time with the decrease of outdoor air temperature and solar radiation. Therefore, the proposed control strategy has a good adaptive ability, compared with the reference one. The proposed control strategy can save energy about 15.4% compared with the reference in case 1; while it can save energy about 24.6% in case 2.

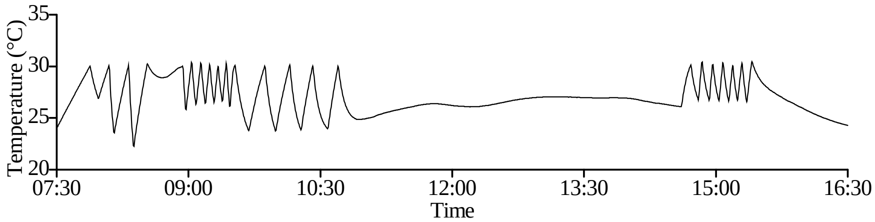

Fig.5 - The indoor air temperature of the proposed control strategy in case 2

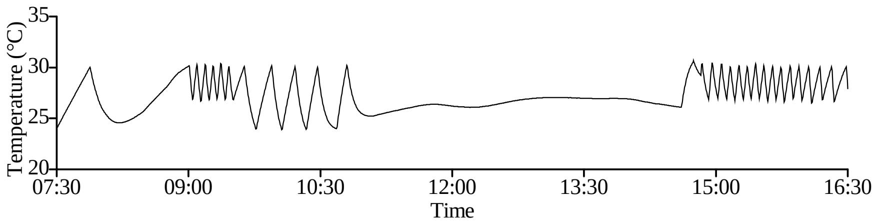

Fig.6 - The indoor air temperature of the reference control strategy in case 2

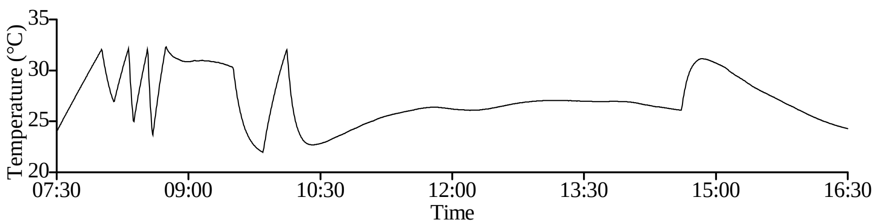

Fig.7 - The indoor air temperature of the proposed control strategy in case 3

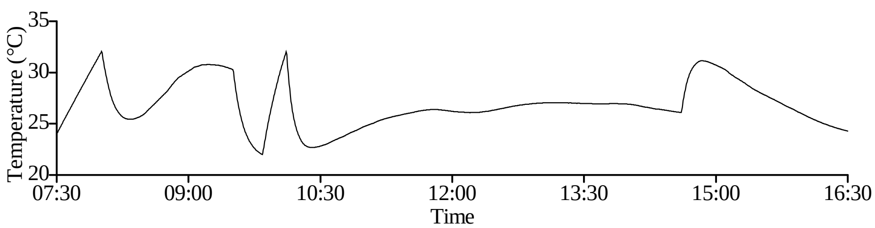

Fig.8 - The indoor air temperature of the reference control strategy in case 3

Table 1

The operating times of cooling modes in both control strategies

Case	Proposed control strategy (min)			Reference one (min)		
	NV	MV	PF	NV	MV	PF
1	400	3	53	371	20	52
2	371	15	33	340	22	42
3	458	3	3	493	0	0

Note: NV natural ventilation; MV denotes mechanical ventilation mode; PF pad-fan cooling mode.

Table 2

Comparison of energy consumption of two control strategies

Case	Proposed control strategy (kW.h)	Reference one (kW.h)	Energy saving [%]
1	5.5	6.5	15.4
2	4.3	5.7	24.6
3	0.5	0	--

The simulation results in case 3 are very different from that in the first two cases. The natural ventilation mode can meet the cooling requirement very well in case 3, so both the control strategies almost don't consume energy. The proposed control strategy consumes a little energy because of the first three fixed cooling actions. It can be seen that the upper limit has a great influence on the energy consumption for greenhouse cooling. The higher the upper limit is, the less the energy consumption will be. According to the temperature integration theory (*Sigrimis et al., 2000*), a short-term high temperature has little effect on crops. Therefore, in some cases, allowing the indoor air temperature to exceed the upper limit briefly will be helpful for energy saving.

According the results in case 1 and case 2, the different energy saving effect indicates that the set temperature bandwidth has influence on the energy saving potential. In case 2, the temperature bandwidth is narrower, while the energy consumption is less. According to previous studies (*Gu et al., 2001*), the indoor air temperature changes in the form of a negative exponential function during the cooling process, and thus the energy for reducing 1°C is more and more as the indoor air temperature is reduced. Therefore, the narrow range is conducive to save energy. However, the simulation results also show that the indoor air temperature fluctuates more frequently in case 2. In fact, the narrow range leads to the frequent switch of operating modes, which means that the facilities are switched on and off frequently. It's important to compromise the above contradictions for growers, because the frequent switch is easy to damage the facilities.

We focussed on the switching control of the three common cooling modes for energy saving, so we didn't study the cooling effect of shading net quantitatively in this paper. The simulation results indicate that the shading net is effective to reduce the energy consumption. In case 1 and case 2, when the shading net is folded, the natural ventilation mode is unable to reduce the indoor air temperature below the upper limit; while when the shading net is unfolded, the natural ventilation mode can meet the cooling requirement well. The influence of shading net is also confirmed by the simulation results in case 3. Therefore, it's necessary to make full use of the shading net for cooling greenhouse in future practice. Before setting the thresholds for shading, the demand of light illumination must be fully considered for the photosynthesis of indoor crops.

CONCLUSIONS

In order to reduce the energy consumption of greenhouse cooling in subtropical and tropical regions, we proposed a switching control strategy based on temperature prediction model for the greenhouses with the facilities driven by the on-off actuators. The simulation results indicate that the control strategy has a good adaptive ability and a good energy saving potential. The control strategy is easy to implement without major revisions on the existing facilities. Even if there are more facilities, the control strategy is still applicable, as long as the operating modes are re-divided and the indoor air temperature prediction models in all modes are constructed. Therefore, the proposed control strategy has a good universality.

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