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Full Length Research Paper

Modeling and analysis of different control strategies for fogging system in a subtropical greenhouse

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A dynamic environment model was established on the effects of greenhouse cooling on different control strategies in a fogging system, which simulations were then conducted by Matlab. Simulation results showed that by applying a suitable set of control strategy, the indoor temperature dropped and was less than the outdoor temperature of 34.4°C The temperature reduction degree changed within limits and delayed time. Inversely, when relative humidity and time delay were used as the control factors, the indoor temperature rose under high solar irradiation. The above phenomenon can be avoided when temperature control was applied. When operations of the fogging system used the dead zone as the setting control, variations of the indoor temperature was mainly relevant to the upper and lower limits of the zone. In situations where the spraying can reach the shutoff condition, the temperature variance increased as the range was larger, and the actuation frequency fogging system also decreased. When the time delay factor was employed in the fogging system, the indoor temperature varied in terms of fogging time and stop time. In order to narrow down the variation of indoor temperature, the operation and stop time in a cycle must be shortened. In this study, simulations with the cooling effects in a greenhouse were performed by using different control strategies for a fogging system. The results can serve as reference for planning future cooling control strategies for a fogging system.

Key words: Greenhouse, fogging system, control strategy.

INTRODUCTION

Protected cultivation not only can reduce the influence of drastic weather changes toward crops, avoid crops being destroyed and prevent loss of hard work, but also has the advantages of adjusting harvesting periods and improving crop quality; therefore, the technique has been gradually used by farmers. Since Taiwan is located in subtropical region, the high solar irradiation during summer often causes increase of temperatures inside the facility, and hinders crop growth. As a result, seeking an effective cooling method inside the facility has always been a striving goal among the greenhouse industry.

Currently, people of the greenhouse industry often apply the principles of evaporative cooling as a method to lower temperatures (Kumar et al., 2009). Arbel et al. (1999) indicated that the practical method can be basically divided into three types: The fan and pad, fan and mist (Chen and Chen, 1994) and fog spray (Huang, 1999, 2000) methods. Although, the fog spray method, when compared to the fan and pad method, for cooling operations inside a greenhouse is less expensive in equipment costs and simpler with installation, it can achieve a better evaporation efficiency (Kumar et al., 2009; Arbel et al., 2003) and a more homogeneous indoor temperature (Reilly, 1994). Furthermore, the method has the advantage of lesser airtight requirements of a greenhouse and suitable for naturally ventilated greenhouse (Hayashi et al., 1998).

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However, in a subtropical climate with inadequate control strategy, the performance of a fogging system is often greatly reduced. For example, when continuous spray operations are performed for temperature cooling, the inside space of an opened-type greenhouse with poor ventilation will often become more stuffy, having the cooling operation become meaningless; whereas in a highly humid environment, excessive spraying will cause spray particles unable to completely evaporate, which water precipitation will cause leaves become wet, and a source of germs and diseases; in addition, if the spraying and interval periods are poorly set in interval spray operations, this may cause the disadvantage which the temperature inside the greenhouse continues to rise (Huang, 2000; Ahmed et al., 2006).

Therefore, in order to avoid inappropriate control strategy which leads to poor performance of the fogging system, this study performed simulation of the fogging system. In the simulations, the ventilation rate and spraying amount were fixed parameters, whereas the amount of solar irradiation was the control parameter, and the evaporation efficiency of spray particles was the variable parameter. The performance of the fogging system based on different control strategies was discussed to serve as a reference for future control strategy designing in fogging systems.

THEORETICAL ANALYSIS

The calculation of the thermal environment within the facility can be divided and discussed into two parts: Conservation of energy and conservation of mass. The conservation of energy was calculated with conservation of heat of the indoor and outdoor environment, whereas mass conservation was based on the conservation of water of the indoor and outdoor environment. In this study, the model was mainly derived according to literature (Albright, 1990; Wang, 1993; Chour and Lin, 1997).

Mass conservation

The factors of water changes within the facility include ventilation, spray evaporative cooling, absolute indoor/ outdoor humidity, and evaporation from crops and soil. From the principle mass conservation, the balance of water within the facility can use the following equation:

$$V \times \rho_i \times \frac{dW_i}{dt} = \beta \times \omega + (W_o - W_i) \times m + \frac{H_g}{h_{fg}} \quad (1)$$

Where, β is the fraction of the evaporated fog; ω is the total fogging rate (kgs^{-1}); W_o is the Absolute humidity outside the greenhouse (kgkg^{-1}); m is the ventilation rate (kgs^{-1}); V is the greenhouse volume (m^3); ρ_i is the density of air inside the greenhouse (kgm^{-3}); W_i is the absolute humidity inside the greenhouse (kgkg^{-1}); H_g is the distribution of latent heat by crops and the soil (W) and h_{fg} is the Latent heat of evaporation (Jkg^{-1}).

The difference between Equation (1) with the dynamic model of Chour and Lin (1997) for simulating the thermal environment inside a barn is that no livestock are inside a greenhouse, and therefore the latent heat term contributed by livestock was removed. In addition, according to the method by Wang (1993) for the calculation of water in crops and soil, a latent heat term for crops and soil was added to calculate the evaporation.

Energy conservation

The conservation for energy is related to the indoor/ outdoor air temperature, enthalpy, and heat transfer, thermal radiation and heat convection of the ground and covering material. The energy conservation of the green-house environment can be expressed by Equation(2):

$$V \times \rho_i \times \frac{dh_{in}}{dt} = (h_{out} - h_{in}) \times m + K_{in} \times A_w \times (T_S - T_i) + A_f \times k_f \times (T_i - T_f) + A_f \times K_q \times (T_f - T_w) \quad (2)$$

Where, h_{out} is the enthalpy of outdoor air (Jkg^{-1}); h_{in} is the enthalpy of indoor air (greenhouse) (Jkg^{-1}); K_{in} is the convection coefficient of the covering material towards indoor air 6.4 (Wm^{-2}℃$^{-1}$); K_f is the convection coefficient of the ground towards indoor air 4.65 (Wm^{-2}℃$^{-1}$) (Wang, 1993); K_q is the heat transfer coefficient of the ground surface towards underground 1.29 (Wm^{-2}℃$^{-1}$) (obtained by Equation (3)); A_w is the area of the covering material (m^2); A_f is the ground area of the greenhouse (m^2) and T_S is the surface temperature of the covering material (℃) (obtained by Equation (4)); T_f Temperature of the ground inside the greenhouse (℃) (obtained by Eq. (5)); T_w Underground temperature (℃); T_{in} Temperature of indoor air (℃).

The difference between Equation (2) with the energy conservation by Chour and Lin (1997) is with the adding of ground heat conduction and heat convection terms. Also, Equation (2) was in accordance to the calculations in previous studies (Wang, 1993; Chandra et al., 1981; Mathala and Gupta, 2002; Tanaka et al., 2004) for heat transfer and heat convection of the covering material. The underground temperature was based on the study by Tanaka et al., (2004), considering the temperature at 1 m below surface.

The heat transfer coefficient between the ground and underground was obtained by calculation with the dry density and saturated conditions of soil:

$$K_q = K_s^{1-n} K_w^{n \cdot s} K_a^{n \cdot (1-S)} \quad (3)$$

Where, K_s is the heat transfer coefficient of soil particles 2.6 (Wm^{-1}℃$^{-1}$); K_w is the heat transfer coefficient of water 0.6 (Wm^{-1}℃$^{-1}$); K_a is the heat transfer coefficient of air 0.024 (Wm^{-1}℃$^{-1}$); n is the porosity (sand) 33.0% and *S* is the saturation coefficient 0.75.

The surface temperature of the covering material was calculated by the heat transfer equation of the covering material Kao (2000):

$$T_S = T_{out} + \alpha \times \left(\frac{Rn_a}{K_{out}} \right) \quad (4)$$

Where, A is the solar energy absorption rate at the material surface 0.65; Rn_a is the outdoor net radiation (Wm^{-2}); K_{out} is the outdoor conductivity of material surface 6.3 (Wm^{-2}℃$^{-1}$) and T_{out} is the outdoor temperature (℃).

For stable solar irradiation with windless condition, neglecting latent heat and sensible heat changes, the ground temperature can be obtained by the following equation:

$$T_f = T_{out} + \left(Rn_{in} - \sigma \times T_{out}^{\ 4} \right) / \left(4 \times \sigma \times T_{out}^{\ 3} \right) \quad (5)$$

Where

$$Rn_{in} = (1 - ref) \times Rn_g + Rn_{lon} \quad (6)$$

The terms in Equation (6) refer to:

Rn_{lon} is the atmospheric long wave radiation, 343 (Wm^{-2}); Rn_g is the solar irradiation amount from sky (Wm^{-2}); ref is the refractive index of farmland, 0.2; Rn_{in} is the net radiation (Wm^{-2}) and σ is the Boltzmann constant 5.67×10^{-8} (Wm^{-2}K^{-4}).

Time calculations for spray particles to completely evaporate

As spray particles evaporate, the particle size will gradually decrease. For a particle of size d, the required time for the particle to completely evaporate can be calculated by the Langmuir equation (Reist, 1993):

$$t = \frac{\rho_w R T d^2}{8 DM \ (P_m - P_{in})} \quad (7)$$

with *D* as,

$$D \approx D_0 \left(\frac{T_{in} + 273.15}{T_0} \right)^{1.94} \quad (8)$$

Where, ρ_w is the water density (0.9971 gcm^{-3} at 25°C); d is the initial size of fog particle (cm); R is the 62,360 (cm^2.mmHg/k.mole); P_m is the vapor pressure of fog at given temperature (T_m) (mmHg); P_{in} is the vapor pressure of air at given temperature T_{in} (mmHg); M is the molecular weight of water, 18 (gram-molecular weight, g/mole); T_0 is the 273.15 (K); D is the diffusion coefficient of water vapor in air and D_0 is the diffusion coefficient of water vapor in air at 0℃, 0.219 (cm^{2}s^{-1}).

The fraction of the evaporated fog

The fraction of the evaporated fog is the percentage ratio of actual evaporation amount of the water with the total fogging amount. Based on the above definition, the calculation of fraction of the evaporated fog in this study was therefore based on the travel distance of the fogging particle as indicator. When the height of the sprinkler installed within the facility is greater than the travel distance of the fogging particle, the fraction of the evaporated fog is indicated as 1; when the travel distance of the fogging particle is greater than the sprinkler height, the fraction of the evaporated fog is referred to the percentage of the remainder particle size to the initial size. Under a windless condition, Equation (9) calculates the travel distance of a spray particle (Chour and Lin, 1997):

$$DIS = at - bm_0 \left(t - \frac{3}{4}\eta \times t \right)^2 - \frac{4}{15\eta} cm_0^{\ 3/2} \left(1 - \frac{3}{2}\eta \times t \right)^{5/2} - \frac{4}{9\eta} dm_0^{\ 1/2} \left(1 - \frac{3}{2}\eta \times t \right)^{3/2} - \frac{4}{3\eta} em_0^{\ -1/2} \left(1 - \frac{3}{2}\eta \times t \right)^{1/2} + \frac{4}{15\eta} cm_0^{\ 3/2} + \frac{4}{9\eta} dm_0^{\ 1/2} + \frac{4}{3\eta} em_0^{\ -1/2} \quad (9)$$

Table 1. Fogging system turned on and shut off conditions set by time.

Number of sets	Fogging turned on time (min)	Interval time
1	1	1 min
2	2	1 min
3	3	1 min
4	1	30 s
5	2	30 s

Table 2. Fogging system turned on and shut off conditions set by indoor temperature.

(Number of sets)	(Stop condition) (℃)	(Start condition) (℃)	(The range of dead zone) (℃)
1	30	34	4
2	31	34	3
3	32	34	2
4	33	34	1

Table 3. Fogging system turned on and shut off conditions set by indoor relative humidity.

Number of sets	Start condition (%)	Stop condition (%)
1	50	80
2	50	70
3	50	60
4	60	80
5	60	70
6	70	80

where,

a = -1.17716
b = -2.12184
c = 0.05065
d = 38.94621
e = 0.00097

$$\eta = \frac{8 \times D \times (C_0 - C_\infty)}{d^2 \times \rho_w}$$

DIS is the travel distance of fogging particle (m); m_0 is the initial mass of fogging particle (g); t is the required time for fogging particle to completely evaporate (s); C_0 is the water vapor concentration at the droplet's surface, can be expressed by absolute humidity of fogging particle × ρ, (gm^{-3}) and C_∞ is the indoor water vapor concentration, can be expressed by absolute humidity of fogging particle × ρ, (gm^{-3}).

MATERIALS AND METHODS

Combination simulations in different control strategies

The common used methods for greenhouse operations in temperature cooling are time control and temperature control. Time control is based on an on-and-off fogging with time intervals for temperature cooling. The combination simulation in this study is shown in Table 1.

Temperature control is based on the setting of temperature upper/lower limits as the condition for on/off fogging. The sprinkler is turned on when the indoor temperature reached the activating condition, and then closed when the indoor temperature drops to the shut off condition. Since this method exists with an on/off setting range where there is no reaction, it is also known as dead zone control.

This combination simulation is given in Table 2. In addition, to avoid a highly humid indoor environment by fogging operations, which will cause crop diseases or inhibition of growth, an indoor relative humidity factor was added as a control condition for simulations. The sprinkler is shut down when the indoor humidity reaches the shut off condition, and is then turned on as the indoor humidity is below the activating condition. This combination

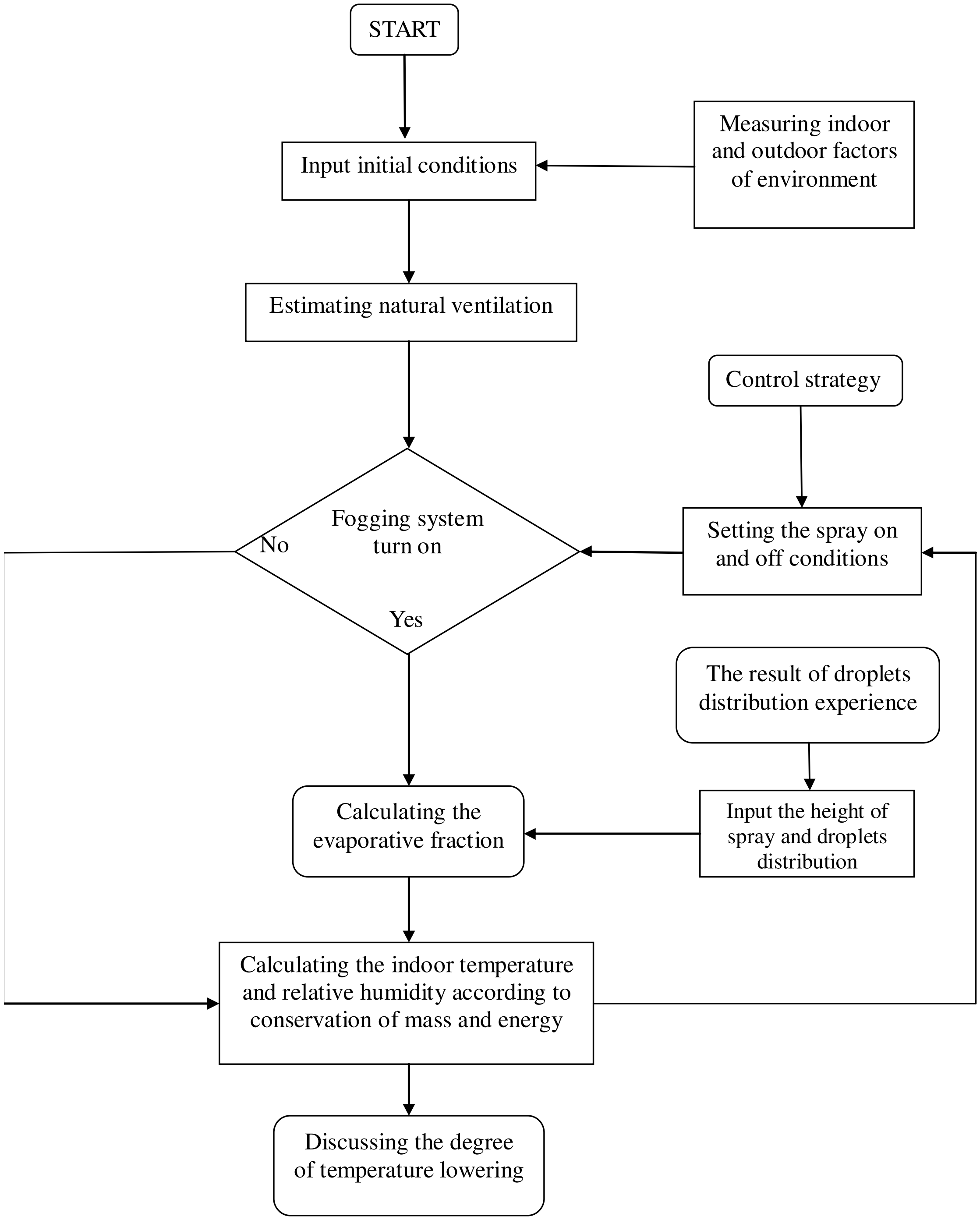

Figure 1. Flowchart showing the simulation procedure.

simulation is given in Table 3.

Dynamic simulation procedure for thermal environment calculations

The simulation equations were written in MATLAB, and the calculating procedures are shown in Figure 1. The calculations required for each step are described as follow:

Estimation of natural ventilation rate and designed evaporation rate

After the sprinklers were activated, the natural ventilation rate was calculated by actual measurement of the initial environmental condition. The initial environmental conditions used in the simulation was based on the measurement by Yu (2002) for the indoor and outdoor environments at PM1:40, July 22, 2002: outdoor air temperature 34.4°C with relative humidity 50%, indoor temperature 37°C with relative humidity 50%, outdoor net radiation 38.6 $kJm^{-2}min^{-1}$, and indoor net radiation 30.9 $kJm^{-2}min^{-1}$. The natural ventilation rate and required spray rate were estimated by the VETH curves of Huang (2000), which were 2.725 $m^3m^{-2}min^{-1}$ and 0.04 kgs^{-1}, respectively.

Determination of on/off fogging conditions

The on/off fogging conditions were determined by the control strategy setting, which the various designing of control strategy combinations are listed in Tables 1 to 3. Under a fixed ventilation condition of 2.725 $m^3m^{-2}min^{-1}$ and fogging rate of 0.04 kgs^{-1}, and using same initial environment conditions, the simulation for temperature cooling was conducted for several minutes with solar irradiation adjusted from 20 ~ 50 $kJm^{-2}min^{-1}$ with an interval of 10 $kJm^{-2}min^{-1}$ for discussing the fogging situation at different amounts of solar irradiation.

Fraction of the evaporated fog

The on/off fogging was determined by control strategy combinations. When the sprinkler was activated, the fraction of the evaporated fog was then calculated. The calculation with fraction of the evaporated fog was initially done with a laser particle size analysis by Malvern Instruments (Model: System 2600). With fogging pressure at 20 $kgcm^{-2}$, the fogging test was conducted based on the method by Huang (1999) to obtain the size distribution of fog particles at the given fogging pressure. The time required for the particle sizes to completely evaporate was then calculated by Equation (7), which the obtained time was then substituted into Equation (9) to calculate the travel distance of each fog particle with its given size. The travel distance was then compared with the setting height of the sprinkler at 2 m to obtain the particle size after evaporation under the given sprinkler height. The fraction of the evaporated fog was then determined by the ratio of the particle size with the initial size. The calculated values were then used within the fogging system simulation.

Results by mass and energy conservation equations

The indoor temperature and humidity after activating the fogging system was then calculated by the mass and energy conservations by Equations (1) and (2). The calculated values were then determined by the activation/shutoff settings in control strategy to determine on/off of fogging. The cycle was performed for several minutes.

RESULTS AND DISCUSSION

Fogging condition by using relative humidity as control strategy

Cooling performance

The cooling situation by using relative humidity as control strategy is given in Table 4. As shown in the table, it can be seen that under the same amount of solar irradiation, the temperature decreased to a lower value as the shut off condition (based on relative humidity) was higher. Therefore, within the allowable range in relative humidity, the shut off condition setting should be increased as possible to achieve a greater temperature cooling effect. Also from the table, it is found that under the same amount of sunshine, the temperature lowing capabilities were equal when the relative humidity setting in the shut off condition were the same, and are shown to be irrelative with the activation condition (relative humidity). Furthermore, very low activation conditions in relative humidity often cause fogging systems to have trouble turning on under Taiwan's climate conditions. In order to enable facility sprinklers to turn on at high temperatures for cooling operations, it is suggested that the activating condition of the fogging should be based on temperature, and combined with relative humidity as the shut off condition. This way both goals of temperature cooling and avoiding too wet can be achieved.

The results in Table 4 showed that under a high amount of solar irradiation at 50 $kJm^{-2}min^{-1}$, the lowest decreasing temperature by shut off conditions 70 and 80% was similar. The reason can be explained by Figures 3 and 4. In Figure 2, with solar irradiation at 50 $kJm^{-2}min^{-1}$ and simulation setting conditions in this study, the final relative humidity only approached 70%, and therefore explains the similarity in temperature cooling performance with a shut off condition at 70% relative humidity. By summarization, it was discovered that the rate of solar irradiation at 50 $kJm^{-2}min^{-1}$ has exceeded the initial design at 38.6 $kJm^{-2}min^{-1}$ and therefore caused insufficiency with spray design. As a result, under this control combination, continuous spraying occurred, which the indoor temperature was about 1°C lower than outside; In addition, it is also seen in Figure 3 that under a high solar irradiation rate of 50 $kJm^{-2}min^{-1}$, the peak and trough values for the indoor temperature variation curve eventually increased with time as the control range was set between 50 ~ 60% relative humidity. This result consists with the research by Huang (2000) and Ahmed et al. (2006), which in the study for interval fogging, the temperature also increased against the trend.

Temperature variance and actuation frequency of fogging system

The indoor temperature variance by relative humidity as control for cooling is shown in Table 5. With the solar irradiation rate at 30 $kJm^{-2}min^{-1}$, the conditions of spray shutoff respectively at 60, 70 and 80% with the activating condition at 50% (for all three) were compared. The variances in temperature were 2.5, 4.5 and 6.25°C, respectively. It can be seen that the variance of indoor temperature was smaller when the control range was narrower. Therefore, based on the need for different control under different amounts of solar irradiation, a suitable control range with relative humidity is to be selected.

Furthermore, the actuation frequency of the fogging system was closely related with the relative humidity control range. When the range for the upper/lower limits

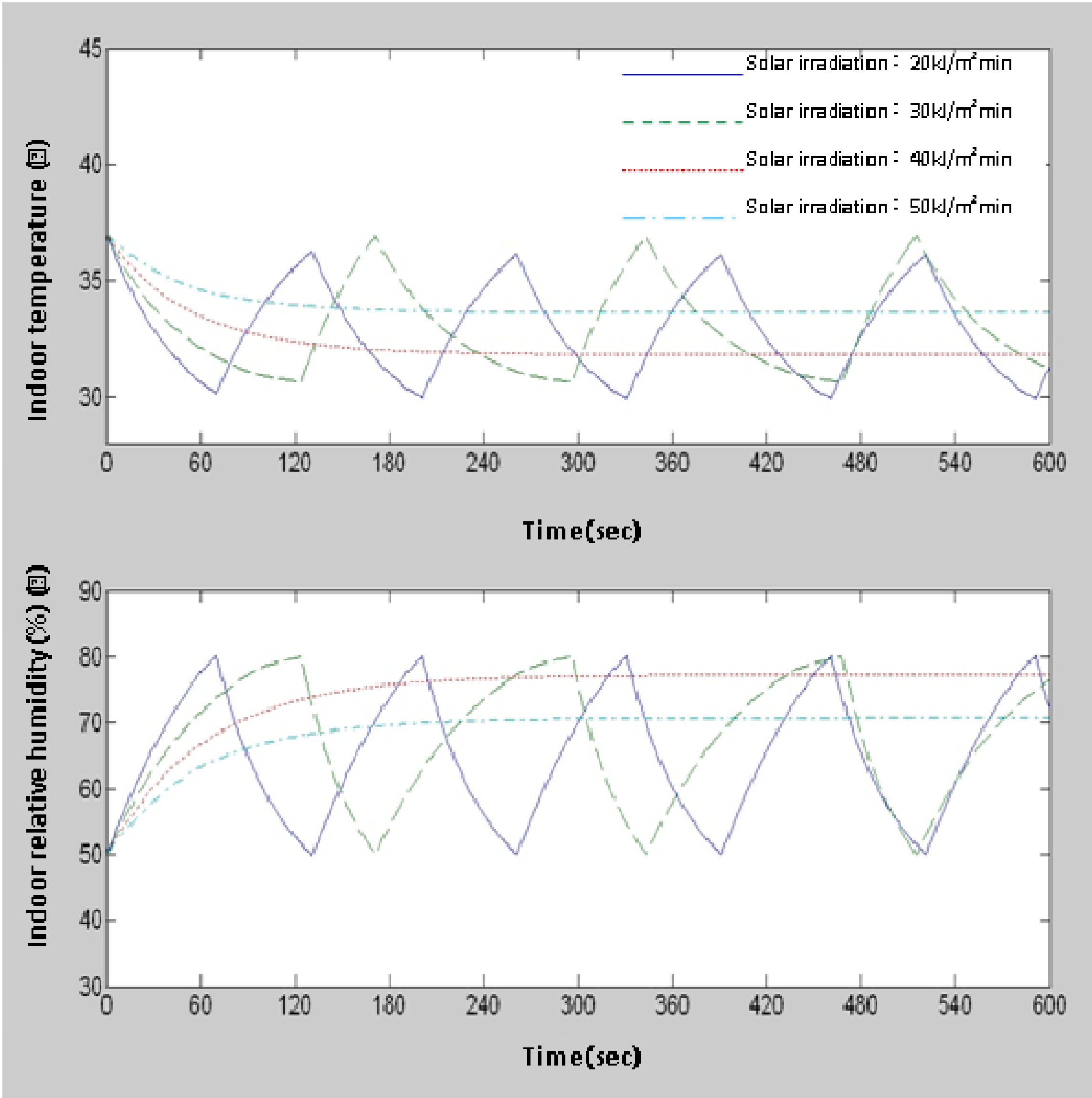

Figure 2. Variation of the inside temperature and relative humidity (fogging on : 50 % RH; off: 80 % RH).

Table 4. The lowest temperature under different relative humidity control strategies.

Start condition (%)	Stop condition (%)	Solar irradiation($kJm^{-2}min^{-1}$)			
		20 (℃)	30 (℃)	40 (℃)	50 (℃)
50	60	33.6	34.3	34.7	35.1
50	70	31.7	32.4	32.9	33.7
50	80	29.9	30.7	31.8	33.6
60	70	31.7	32.4	32.9	33.7
60	80	29.9	30.7	31.8	33.6
70	80	29.9	30.7	31.8	33.6

of control was narrower, the number of actuation was more frequent whereas a larger control range resulted with less actuation. Also, when the relative humidity setting for the shutoff was greater, the number of actuation became more and more frequent as the control range became smaller, as in Figures 2 and 3. The results

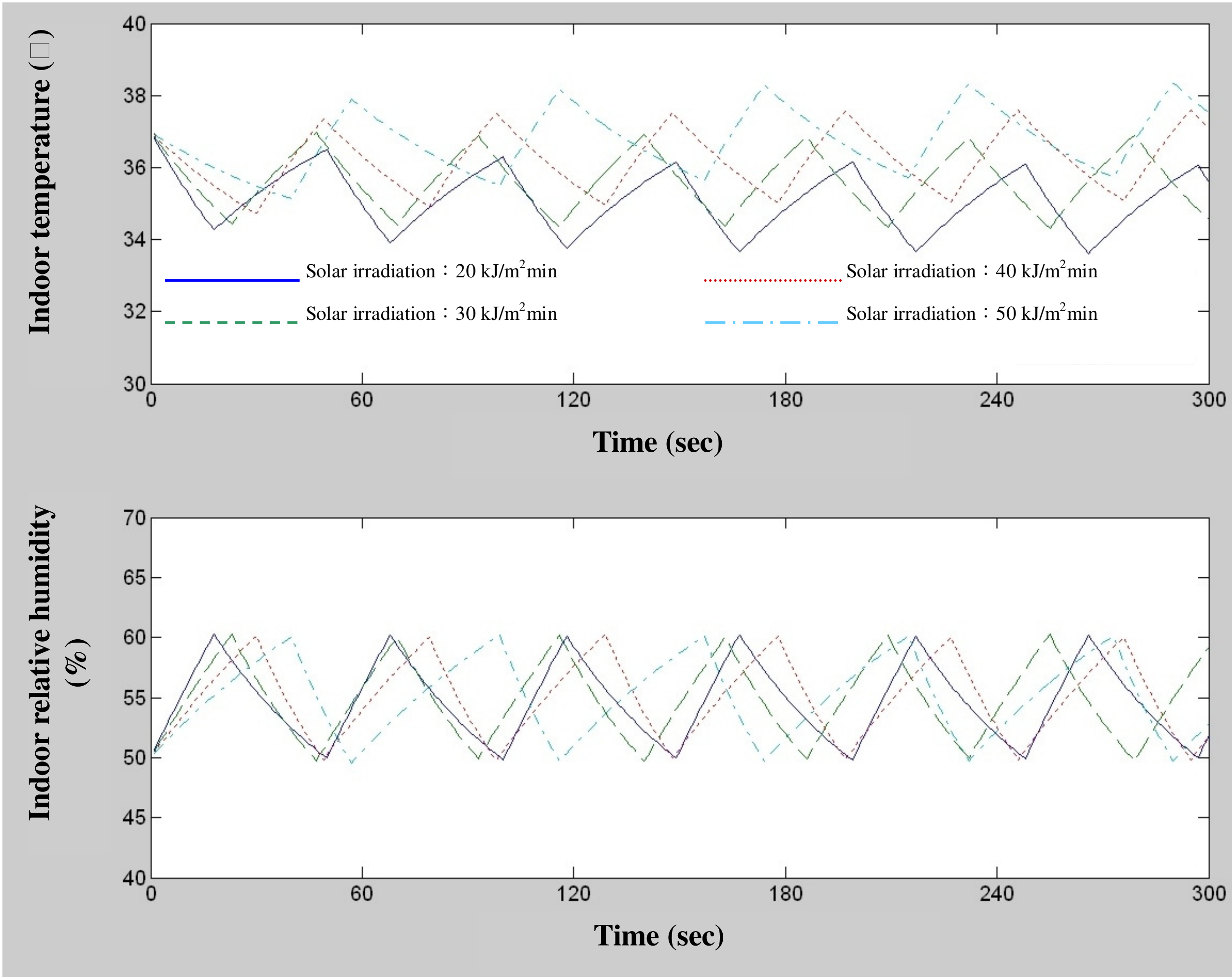

Figure 3. Variation of the inside temperature and relative humidity (spray on: 50 % RH; off: 60 % RH).

Table 5. Variation of temperature under different relative humidity control strategies.

Start condition (%)	Stop condition (%)	Solar irradiation ($kJm^{-2}min^{-1}$)			
		20 (℃)	30 (℃)	40 (℃)	50 (℃)
50	60	2.38	2.5	2.57	2.56
50	70	4.41	4.5	4.6	4.7
50	80	6.13	6.25	-	-
60	70	2.07	2.16	2.24	2.13
60	80	3.83	3.9	-	-
70	80	1.81	1.82	-	-

are exactly the opposite with temperature variation control. Therefore, under this control strategy design, considerations are to include the crops' bearing ability in temperature changes, the most suitable growth condition, and actuation frequency of the equipment in order to create a growing environment for crops under an optimal economic method.

Fogging condition by using indoor temperature as control strategy

Cooling performance

For fogging simulations by setting a temperature range as control, the temperature cooling level should be as

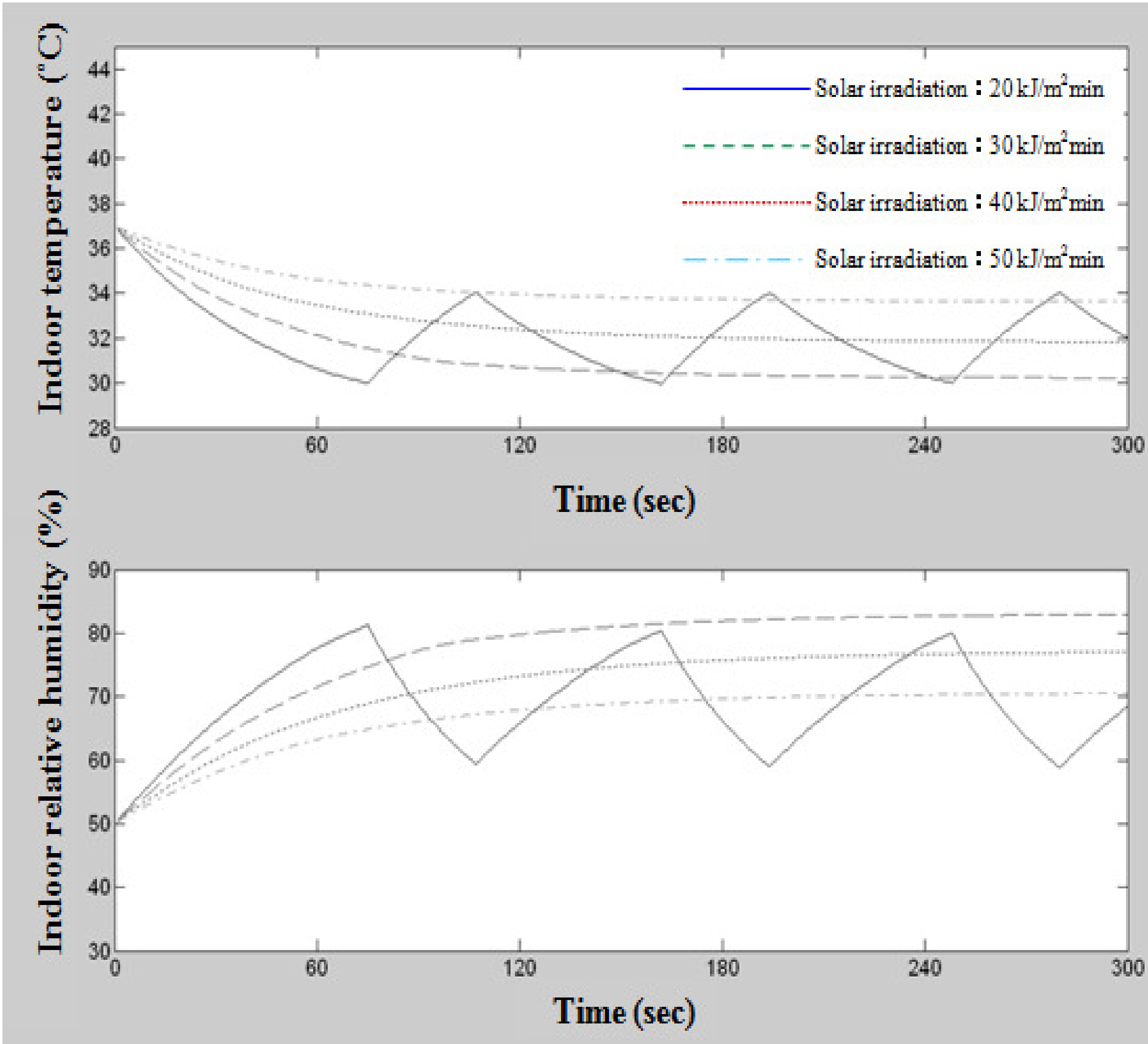

Figure 4. Variation of the inside temperature and relative humidity (spray on : 34℃ d.b.; off : 30℃ d.b.).

same with the shut off condition. However, continuous spraying occurred for high amounts of solar irradiation and a shutoff spray setting that is too low. The reasons for the phenomena are the same in using relative humidity control as strategy, which is because of insufficient design with the spraying amount. An example is described by Figure 4, which a fixed spraying amountat 0.04 kgs^{-1} under different sunshine conditions was used for simulation. The results show that only when the amount of solar irradiation was under 20 $kJm^{-2}min^{-1}$ would the indoor temperature reach the shutoff condition at 30˚C. When the amount of solar irradiation was 30, 40 and 50 $kJm^{-2}min^{-1}$, cooling operations were under continuous spraying.

After a certain time, the indoor temperatures were respectively balanced at 30.3, 31.7 and 33.6˚C. If we assume that the growing condition of the crops inside the facility were required to be less than 30˚C, then the spray amount must increase in order to lower the room temperature to the growing condition. In addition, for a fogging system based on this control strategy, the system is instantly activated when the temperature reaches 34˚C, as the activating condition is controlled by temperature. This can effectively prevent temperature rising against the trend, as shown in Figure 3.

Temperature variance and actuation frequency of fogging system

When on/off spraying was based on the setting of indoor temperature as control, the variations of indoor temperature was mainly related to the setting range. When the shutoff condition of the spray is reached, then temperature variance equals to the temperature difference between the upper and lower limits in control. The

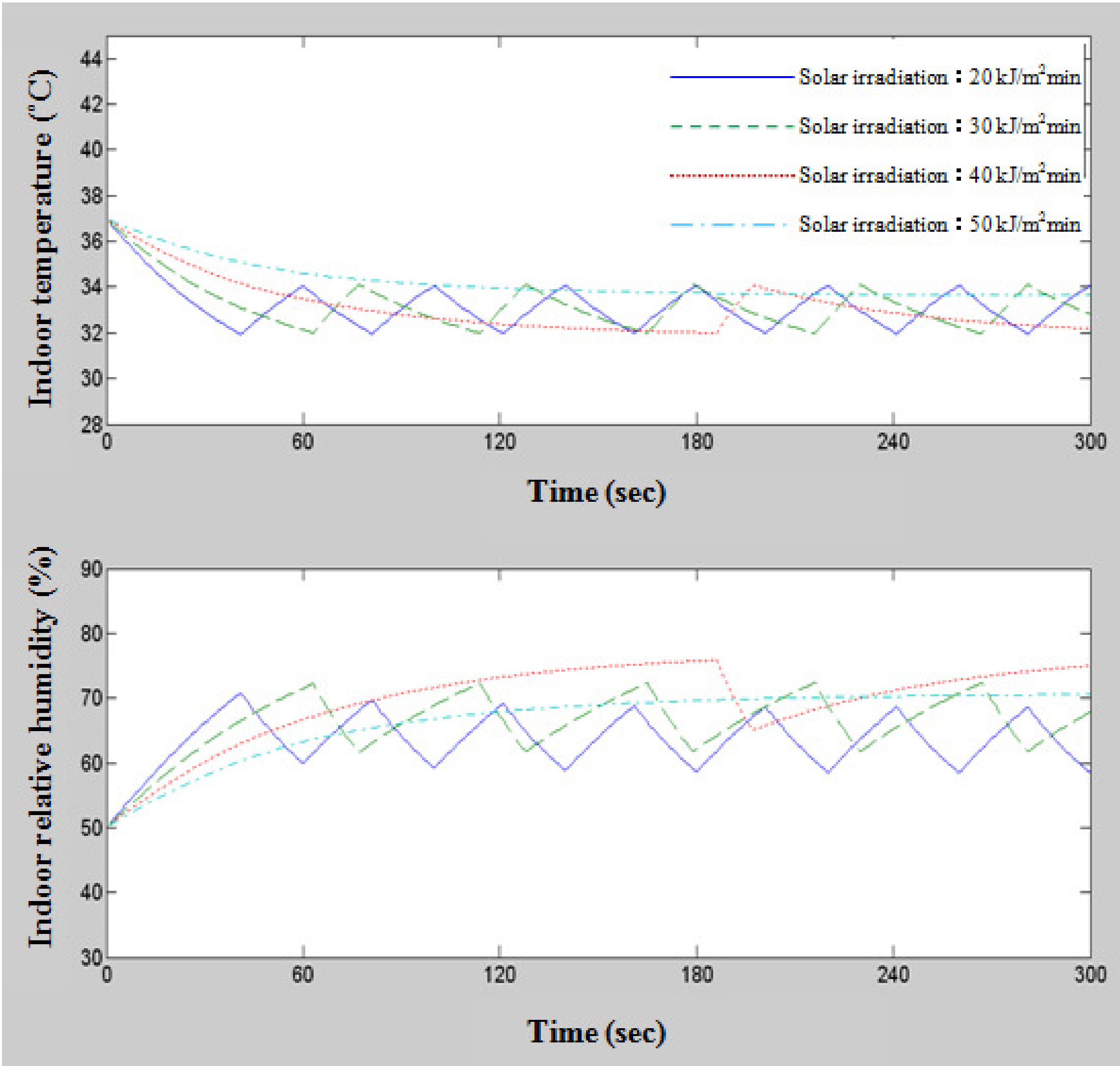

Figure 5. Variation of the inside temperature and relative humidity (spray on: 34℃ d.b.; off: 32℃ d.b.).

system's actuation frequency was also related with the setting range of the control. A comparison of Figures 4 and 5 show that for solar irradiation at 20 $kJm^{-2}min^{-1}$ and using the same simulation time of 300 s, the number of actuation by the temperature control setting between 34 ~ 30˚C was about 4 times, whereas it was about 7 times for the fogging system with a temperature control range at 34 ~ 32˚C. The simulation showed that the system's actuation was more frequent with a narrower control range.

Fogging condition by using spraying periods as control strategy

Cooling performance

The duration length of spraying affects the drop level of the temperature, as in Table 6. As shown in the table, when the amount of solar irradiation was 20 $kJm^{-2}min^{-1}$, with a pattern of spraying for 2 minutes with 1 minute interval, the temperature was able to drop to 28.89℃. When the pattern was spraying for 1 min with 1 min interval, the temperature only dropped to 30.4˚C, having a 1.51℃ difference with the previous method. This indicates that the level of the temperature drop was greater as the spraying duration was longer, whereas the temperature dropped was less when the spraying duration was shorter. An additional comparison was performed for spraying time of 3 min with 1 min interval; which the result had little difference with the spraying time of 2 min with 1 min interval. This phenomenon can be explained by the variation curves of indoor temperature and humidity in Figure 6. After 2 min of spraying, the temperature had reached a steady temperature, which extended spraying has limited effects in cooling.

Table 6. The lowest temperature under different sets of fogging periods.

Fogging time	Interval time	Solar irradiation (kJm^{-2}min^{-1})			
		20	30	40	50
One minute	One minute	30.4 ℃	32.12 ℃	33.48 ℃	34.59 ℃
Two minutes	One minute	28.89 ℃	30.7 ℃	32.39 ℃	33.96 ℃
Three minutes	One minute	28.77 ℃	30.38 ℃	32.01 ℃	33.74 ℃
One minute	Thirty seconds	30.02 ℃	32.03 ℃	33.62 ℃	34.66 ℃
Two minutes	Thirty seconds	29.07 ℃	30.95 ℃	32.7 ℃	34.24 ℃

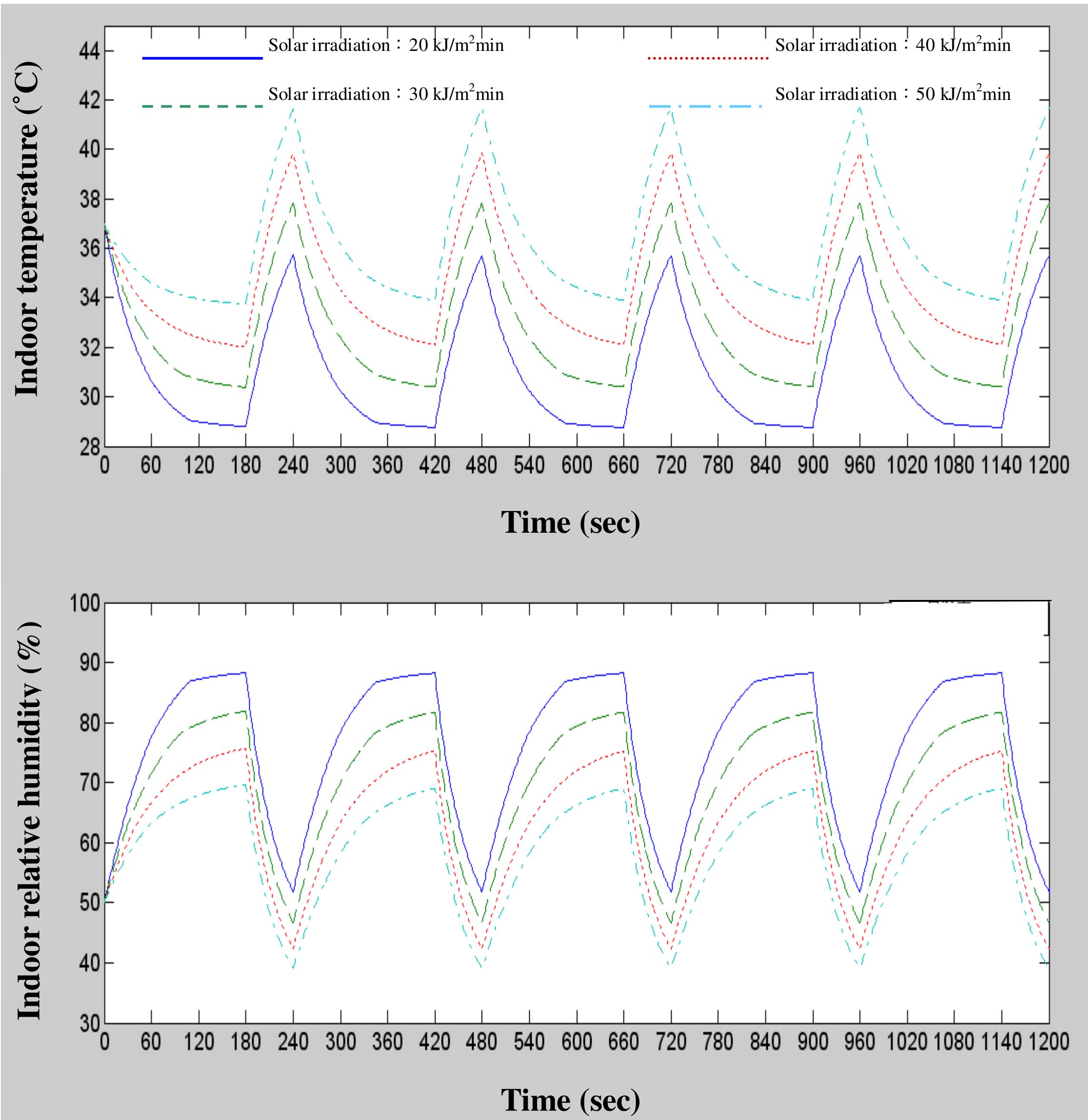

Figure 6. Variation of the inside temperature and relative humidity (fogging on: 3 min and interval: 1 min).

Furthermore, with a low amount of solar irradiation at 20 kJm^{-2}min^{-1}, the indoor relative humidity reached as high as 87%. The highly humid environment caused the chances of spray particles precipitate to the ground to

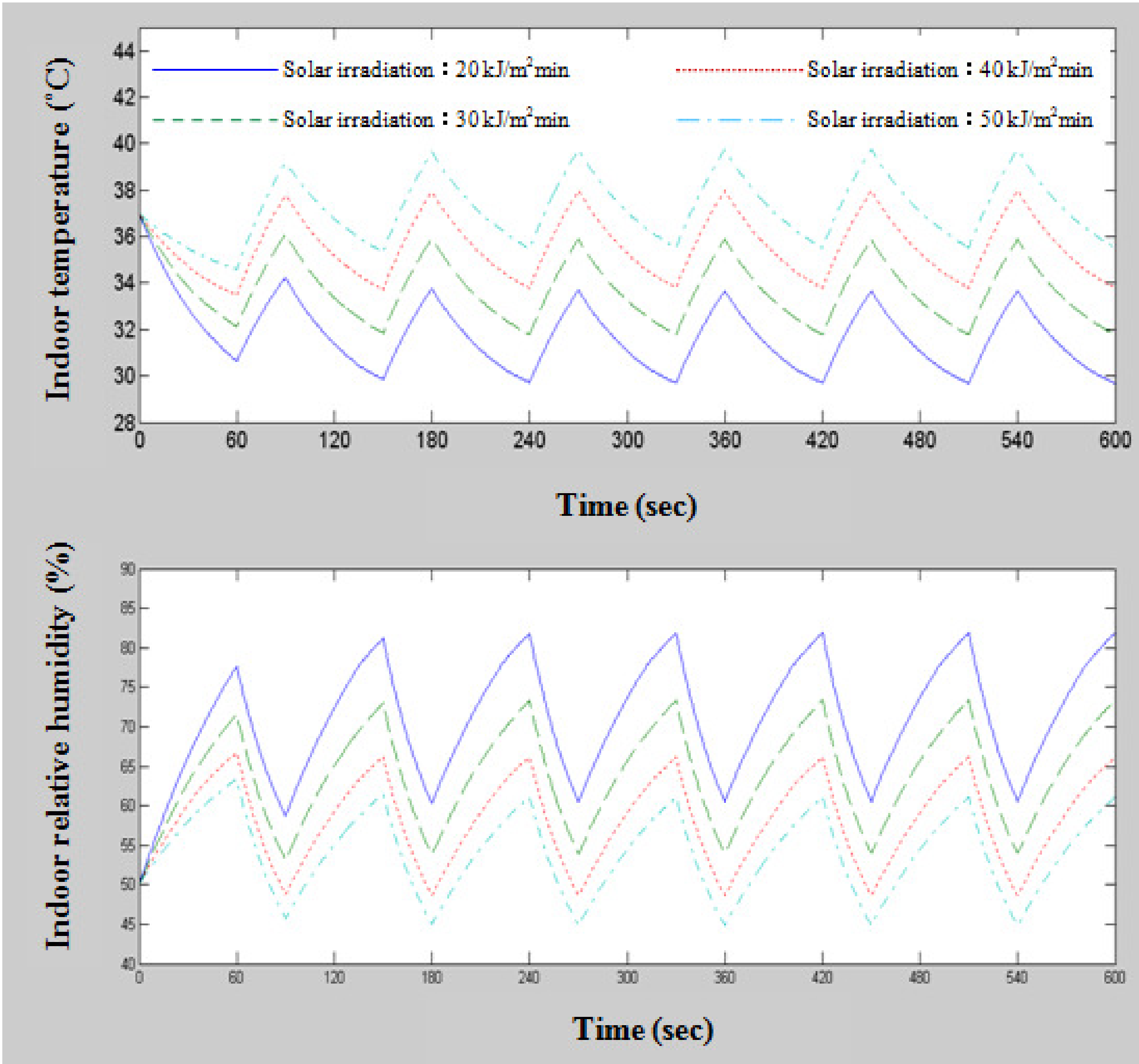

Figure 7. Variation of the inside temperature and relative humidity (fogging on: 1 min and interval: 30 s).

increase. If the environment has poor ventilation, this will easily cause excess moisture with the indoor ground and the leaves of crops, and further become a source of germs and diseases. Therefore, the spraying period cannot be unlimitedly extended, especially when there are low amounts of solar irradiation which excessive spray time periods will cause a highly humid environment and unfavorable for crops to grow. The figure also indicates that the effectiveness of the fogging system decreases at the rear segments of long spraying periods. Therefore, a suitable spraying period should be determined to obtain the optimal performance with the fogging system.

In addition from Figure 7, it can be seen that the results will totally differ when the same control strategy was applied to situations of different amount of solar irradiation. For example, when solar irradiation was 20 $kJm^{-2}min^{-1}$, interval spraying enabled the temperature to eventually drop, whereas with 50 $kJm^{-2}min^{-1}$ of solar irradiation, the temperature contrarily increased with interval spraying. Therefore, when the interval spray method is used for cooling operations, the spraying and interval time should be adjusted according to the changes of solar irradiation to avoid temperatures from rising.

Temperature variance

From Table 7, it can be seen that temperature variance depends on the length of the spraying and interval periods. When the interval was 1 min, the variance in temperature as the spraying time was longer; the

Table 7. Variation of temperature under different sets of fogging periods.

Fogging time	Interval time	Solar irradiation ($kJm^{-2}min^{-1}$))			
		20 (℃)	30 (℃)	40 (℃)	50 (℃)
One minute	One minute	5.84	6.1	6.37	6.58
Two minutes	One minute	6.83	7.21	7.45	7.59
Three minutes	One minute	6.94	7.43	7.74	7.79
One minute	Thirty seconds	3.78	3.98	4.14	4.25
Two minutes	Thirty seconds	4.2	4.44	4.6	4.69

temperature variance was also greater as the amount of solar irradiation increased; in addition, when the total spraying period was longer, the temperature variance was also greater. For example, when the total spraying period was 4 min, the temperature variance at solar irradiation of 50 $kJm^{-2}min^{-1}$ reached 7.79℃.

Furthermore, shortening the interval time reduced temperature variance. For example, with a spraying time of 1 min with 30 s interval at solar irradiation of 50 $kJm^{-2}min^{-1}$, the temperature variance was 4.25℃. When compared to the spraying time of 1 min with a 1 min interval, the temperature variance was lesser by 2.33℃. This showed that by shortening the interval time the tem-perature variance can be greatly reduced. Therefore if one intends to reduce temperature variance caused by interval spray operations, the total spraying period should be shortened and interval time reduced.

Conclusions and Suggestions

In this study we establish a dynamic environmental pattern inside a greenhouse to perform simulations based on different control strategies for the fogging system. We then discussed the cooling performance and temperature variance inside the greenhouse based on different strategy combinations. The results may serve as reference for planning future control strategies in fogging systems:

(1) When humidity was used as the factor for dead zone control, the cooling performance was related to the spray's shutoff condition and irrelevant to the spray's activating condition. Also, the temperature cooling performance was more significant when the condition level was higher. Therefore to enhance cooling performance, the shutoff condition value should be increased within the allowable range in relative humidity.

(2) When temperature was used as the factor for dead zone control and with sufficient spray amount, the temperature cooling performance should equal to the setting of the spray's shutoff condition value. Under this type of control strategy, the spray's activating condition is controlled by temperature. As the temperature reaches the setting value, the system instantly activates. This can effectively prevent the temperature from continuously rising.

(3) When a time control, interval spraying was used for cooling, the quality of the environment inside the facility easily becomes unsuitable as the method does not apply environmental factors as a control condition. For example, excessive periods of spraying causes the increase of indoor humidity, resulting with serious precipitation and accumulation of spray particles; inappropriate actuation and interval durations will cause the temperature continue to rise even when spraying is applied. It is suggested that the spraying and interval time should be adjusted according to the changes of solar irradiation to avoid temperatures from rising.

(4) Under high amounts of solar irradiation and lacking of sufficient spraying amounts, an inappropriate spray control strategy will cause the temperature to increase against spraying; to avoid this phenomenon, it is suggested to apply multiple environmental factors as the on/off conditions for spraying, which the spray's activating condition is based on temperature, combined by relative humidity as the shutoff condition. This achieves the function of temperature cooling and avoids the facility becoming too wet.

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